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Contacts: Bernard Pinty & Hugo Zunker

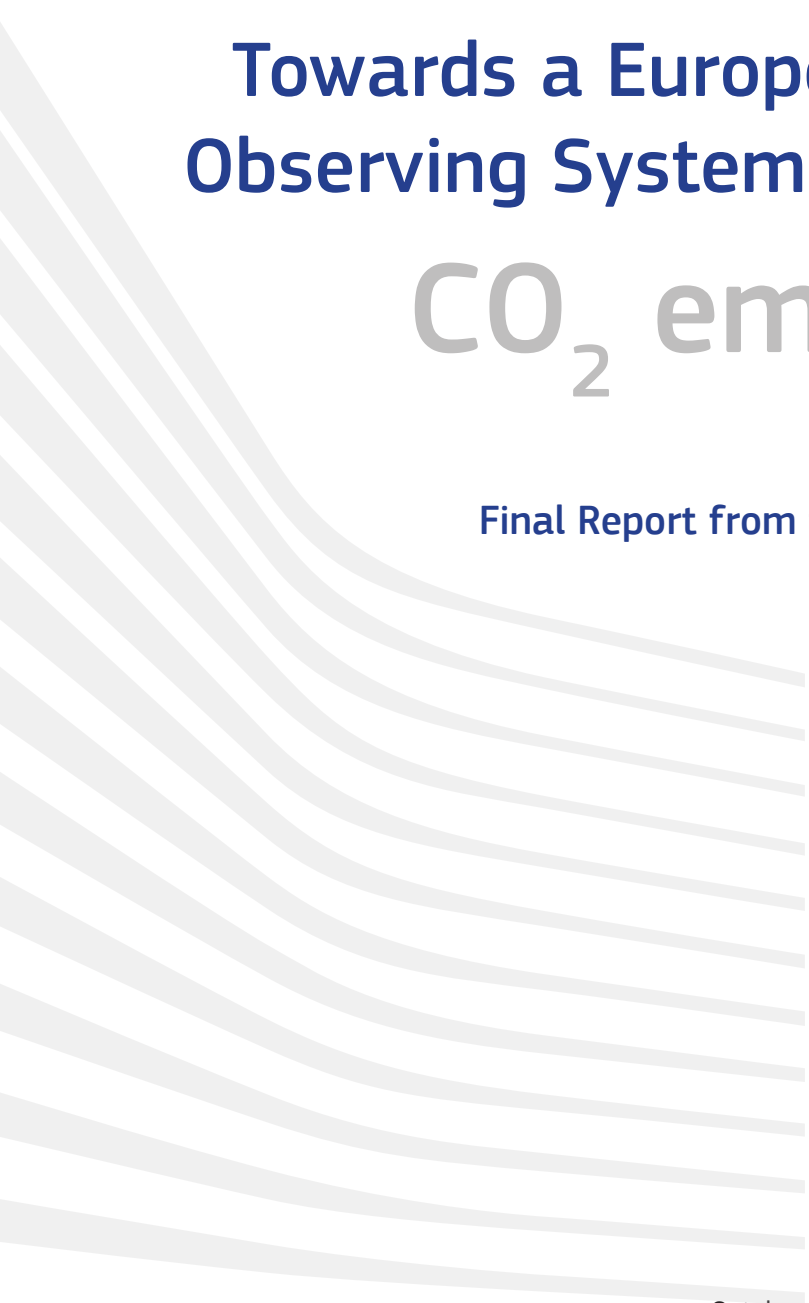
E-mails: Bernard.PINTY@ec.europa.eu

Hugo.ZUNKER@ec.europa.eu

GROW-I2@ec.europa.eu

European Commission

B-1049 Brussels



Towards a European Operational Observing System to Monitor Fossil CO₂ emissions

Final Report from the expert group

Composition of the expert group

Philippe Ciais, Lead author

Head of the LSCE department Biogeochemical cycles and flows in the environment, Gif-sur-Yvette, France; Professor at the University of Paris and of Versailles – St. Quentin, France

David Crisp

Leader of the NASA Orbiting Carbon Observatory-2 (OCO-2) Science Team, NASA Jet Propulsion Laboratory, Pasadena, United States of America

Hugo Denier van der Gon

Project leader of the TNO department Climate, Air & Sustainability, Utrecht, The Netherlands

Richard Engelen

Deputy Head of the ECMWF Copernicus Atmosphere Monitoring Service, Reading, United Kingdom

Greet Janssens-Maenhout

Project leader at the JRC Institute of Environment & Sustainability, European Commission, Ispra, Italy

Martin Heimann

Director at the Max Planck Institute for Biogeochemistry, Jena, Germany, Professor at the University of Jena and of Helsinki, Finland

Peter Rayner

Professor at the University of Melbourne on Data Assimilation and Biogeochemistry, Melbourne, Australia

Marko Scholze

Docent at the Lund University, Department of physical Geography Ecosystem Science, Lund, Sweden

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Technical coordination

European Commission

Directorate-General (DG) for Internal Market, Industry, Entrepreneurship and SMEs

Bernard Pinty and Hugo Zunker

Desk officers in charge of the Copernicus Climate Change Service (C3S) in the Copernicus Unit

Valérie Hoorne

Editorial support in the Space Data for Societal Challenges and Growth Unit

European Commission

Directorate-General (DG) Joint Research Centre (JRC)

Greet Janssens-Maenhout

Technical coordination, Institute for Environment & Sustainability at the Air and Climate Unit

Sophie Barbier

Administrative assistant at the Institute for Environment & Sustainability at the Land Resource Management Unit

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The present expert report was prepared following a request from the Copernicus Unit of DG for Internal Market, Industry, Entrepreneurship and SMEs of the European Commission. The overarching objective of this report is to assess the need and opportunity for an independent European space-borne observation capacity for CO₂ to monitor and to verify the compliance of parties to international climate agreements.

Such a capacity would provide the European Union with a unique and independent source of actionable information, which would address multiple stages of the policy cycle. This would include: in the definition phase, an overview of baseline reference conditions and interpretation of the spatial/geographic implications of proposed targets, in the implementation phase, critical independent information relating to monitoring, reporting and verification activities and, finally, in post-evaluation exercises on the impacts of the implemented policies. Through these various stages of the policy cycle the data provided by this capacity would undoubtedly be integrated with other data (from additional sources, such as emissions inventories) and models, but the high quality synoptic perspective from a dedicated large scale initiative would provide an unprecedented asset to the European Union in pursuing its ambition and meeting its commitments.

The Copernicus programme constitutes the most appropriate frame for supporting an operational European carbon dioxide (CO₂) space initiative through its space component and its Climate Change Service component. Within the latter a possible need for a European satellite-borne observation capacity to monitor fossil fuel CO₂ emissions at global, European and country scales has been identified. A dedicated group of scientific and technical experts has been set up to help the Commission to assess the relevance of a system aiming at the monitoring of anthropogenic emissions, involving notably the current ground based inventories, the joint in situ and satellite observations together with adequate operational interpreting methods.

The salient points of the report delivered by the expert group are addressing the following high-level questions:

- What are the critical uncertainties and limitations of current inventories of fossil CO₂ emissions based on fuel use statistics?
- How could inventories be improved using independent space-borne measurements of atmospheric CO₂?
- What are the current capabilities of space-borne and in-situ ground-based measurements of atmospheric CO₂ in Europe and worldwide?
- How should these capabilities be optimised into an operational system for an independent monitoring of fossil CO₂ emissions and for improving current estimates at the global, European and country scales?
- What are the critical elements and a possible road map for setting up such a system enabling first operational exploitation at the horizon of the 2030s?

Accordingly the current report proposes an implementation strategy for a European initiative that includes a space-borne observation capacity contributing to a system with full operational capabilities at the horizon 2030 and beyond.

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Executive Summary

This report aims to provide a vision and a strategy for a European integrated observation system dedicated to the monitoring of fossil carbon dioxide (CO₂) emissions, with independent atmospheric observations. The construction and operation of this system should be undertaken within the Copernicus programme.

The satellite and in-situ atmospheric measurements described in this report will enable the accurate, transparent and consistent quantification of fossil CO₂ emissions and their trends at the scale of megacities, important industrial sites, small regions, countries, and the Earth as a whole.

Atmospheric measurements will be used in an operational system that comprises three complementary components:

- 1- Atmospheric CO₂ measurements obtained from dedicated space-borne sensors, complemented by in-situ networks, which both allow for the separation of fossil CO₂ emissions from natural fluxes;
- 2- The operational provision of bottom-up fossil CO₂ emission maps, with high spatial and temporal resolution, and near real time updates;
- 3- An operational data-assimilation system, which will integrate atmospheric measurements with bottom-up information into consistent and accurate estimates of fossil CO₂ emissions and their trends.

This report identifies current and future scientific and technical capacities that could enable such an observation system, with operational and internationally coordinated capabilities in the 2030s.

The capacity provided by such a system will provide the European Union with a unique and independent source of actionable information, which would address multiple stages of the policy cycle. Further, this capacity will contribute to a system at global level through integration with similar efforts from third parties.

Context

Current efforts to limit and reduce fossil CO₂ emissions¹, whether they are voluntary or part of international agreements, use self-reported data to the United Nations Framework Convention on Climate Change (UNFCCC) to define baselines and assess the effectiveness of climate and energy policies over time. Self-reported inventories of CO₂ emissions are primarily based on energy-use statistics collected for different sectors. They offer limited transparency and their accuracy and completeness cannot be assessed independently.

In order to monitor the effectiveness of any future climate agreement, self-reported emissions data will need to be independently assessed for their accuracy and reliability. The UNFCCC principle is of “common but differentiated responsibilities” for defining emissions reductions in different countries. In 2015, all countries will report their national emission pledges as Intended Nationally Determined Contributions (INDCs), which are expected to become the basis of a future international agreement on climate change.

¹ In this report we focus on the CO₂ emissions arising from anthropogenic activities, which constitute an addition of exogenous carbon in the climate system. We define “fossil CO₂ emissions” as the sum of CO₂ emissions from fossil fuel combustion, process CO₂ emissions from cement production, process CO₂ emissions from metal (ferrous and non-ferrous) production, and the CO₂ emissions from urea production, urea application and agricultural lime. Emissions from the combustion of biofuel (carbon neutral over one year) and from large-scale biomass burning (forest fires, peat fires) are not included.

All INDCs are based on inventory data, although they take very diverse forms, e.g. based on different sectors, different baseline years, make different hypotheses of future economic development, and different accounting approaches.

In this context, it is critical that emissions baselines and future reduction efforts can be compared among nations on the basis of transparent, consistent, verifiable and up-to-date information. In the past two decades, evidence of sustained climate change and its negative impacts on human welfare has fostered a consensus among nations to act collectively to reduce emissions in the future. During the same period, fossil CO₂ emissions have continued to increase, and in 2014, they were 55% above the levels of 1990.

The recent increase in emissions since the late 1990s has occurred mainly in developing nations, which contributed 60% of the global emissions in 2013, as compared to 32% in 1990, the baseline year of the Kyoto Protocol. Because emission inventories in developing nations are less accurate than they are in developed countries, the uncertainty associated with fossil CO₂ emissions and their trends has increased up to the point where it could undermine the credibility and the stability of future climate agreements.

The INDCs of emission reduction pledges that will form the basis of a future climate agreement require robust emissions mitigation efforts, as well as the monitoring of energy- and fossil-fuel intensive national and global activities under a Measurable Reportable and Verifiable Structure.

Roadmap

This study concludes that it is relevant and timely to develop an operational capacity-driven system to observe and to monitor fossil fuel CO₂ emissions. Such a capacity should be developed within the Copernicus programme and be set-up in three successive phases:

Phase-1 Setup of integrated data infrastructure. The first three years of the project will focus on the integration of existing remote-sensing, in-situ and modeling capabilities, system design and requirements including end-to-end uncertainty assessment, and on the improvement of bottom-up inventories to ensure faster update and higher spatial and temporal resolution.

Phase-2 Pre-operational phase - first satellite mission. This phase will be a requirement-driven and user-driven pre-operational phase centered on the development of a first European satellite mission that will deliver the first high resolution satellite data to quantify fossil CO₂ emissions. The data from this mission will be combined with ground-based inventories by a dedicated data assimilation system, to deliver a first set of improved emission estimates at national and sub-national scale. International cooperation including data sharing agreements and the definition of optimized plans for the setting up of a global observation system, will enable the assimilation of additional satellite data, e.g. from existing and planned US (OCO-2, OCO-3), French MICROCARB (CNES), Chinese (TanSat) and Japanese (GOSAT, GOSAT-2) missions.

Phase-3 Operational Phase. Phase-3 will develop the operational phase initiated in Phase-2 with additional in-situ networks capabilities in Europe, the USA, Asia and other emitting countries, to monitor trends and spatial details of fossil fuel CO₂ emissions. In this phase, routine observations of in-situ tracer data (radiocarbon isotope in CO₂) which enable to separate fossil emissions from natural fluxes, and a set of complementary space-borne sensors, most probably a set of Low Earth Orbit (LEO) satellites, possibly complemented by Geostationary Earth Orbit (GEO) imagers will feed into a fossil emission operational data assimilation system. Dense top-down sampling of the fossil fuel CO₂ signal in the atmosphere, in space and time, will enable the tracking of fossil fuel emissions with a level of accuracy compliant with policy needs.

² The term “bottom-up” is used for emission inventories obtained by aggregating statistical data from relevant economic sectors at a given terrestrial scale (e.g. city, county) relevant for mitigation policy; see Chapter-1.

³ The term “top-down” refers to the approach to determine sources and sinks of greenhouse gases from observations of the atmospheric concentration variations of these gases; see Chapter-2.

The abovementioned schedule is driven by the development of, and long lead-times for some system components. The development and support of an operational system will require a new approach and management, sustained funding and support, as well as technical advances and the development of purpose-built components that meet the requisite specifications.

Expected benefits

The development of a policy-relevant fossil CO₂ emissions observation system will have the following benefits:

- Reinforce the leadership of Europe in the context of international agreements, by helping to determine defensible and feasible emission reduction pathways, and assessing their effectiveness over time.
- Become an essential service to the UNFCCC to provide the roster experts, reviewing the national inventories and reports, with the independent info on e.g. CO₂ emissions trend for certain activities.
- Become a key contribution to international global assessments of CO₂ emissions, e.g. from the International Energy Agency, the Emission Database for Global Atmospheric Research (EDGAR) of the Joint Research Center of the European Commission, the Global Carbon Project and the International Panel on Climate Change periodic assessment reports.
- Improve the inter-operability with other carbon observation systems, contributing to the new GEO Strategy and the new GEO 10 years Implementation Plan (IP) for 2016-2025.
- Facilitate the development of regional and city-scale carbon markets and voluntary emission reductions, based on transparent scientific data delivered by the system.
- Maintain economic competitiveness and create jobs in the high-tech industry, in the fields of data mining and management, space-borne and in situ sensors development.
- Foster international collaboration in an emerging field of Earth Observation, in particular with the USA, Japan and China, who will launch several satellites dedicated to CO₂ monitoring from space during the coming decade.
- Foster technological and scientific research capacity building in Europe.
- Deliver as a by-product of fossil CO₂ emissions, time-dependent maps of biogenic fluxes based on atmospheric measurements, since the envisioned system will have the capacity to separate biogenic from fossil sources. This by-product is expected to bring valuable scientific data on natural CO₂ fluxes, in support of land-based carbon accounting methods and terrestrial carbon cycle models.

Outline of the report

Chapter-1 examines the current uncertainty of the latest fossil CO₂ bottom-up² emission inventories of EU and other nations, at global, national and sub-national scale, including large cities, a growing number of which have declared ambitious voluntary emission reduction objectives that could, in the future, contribute significantly to national mitigation efforts. The limitations of inventories are analyzed in terms of their lack of transparency and of independent emission-related data, as well as in terms of their update and reporting frequency.

Chapter-2 presents the principle of the top-down³ atmospheric approach, which provides independent data to improve emission estimates. It focuses on the key space-based and in-situ-based components of an observation system that make it possible to separate fossil CO₂ from CO₂ exchanged by natural reservoirs (vegetation, soils, oceans). Two complementary approaches are envisioned namely: 1) measuring emission hotspots at the scale of megacities and power plants, and 2) separating fossil CO₂ emissions from biogenic fluxes at regional scale using specific atmospheric indicators of fossil CO₂ such as radiocarbon (¹⁴C in CO₂).

Chapter-3 describes the capabilities and current plans for space-borne instruments dedicated to atmospheric column GHG measurements for CO₂ and methane (CH₄) as well as the specific attributes of CO₂ instruments that would enable the quantification of fossil emissions. To accurately monitor CO₂ emissions with space-borne sensors, high spatial resolution (small footprint size of up to 3 km and imaging capabilities), high accuracy of individual column CO₂ measurement (≈ 1 ppm) are needed across all emitting regions of the globe, as specified in the Product Validation and Intercomparison Report under ESA's Climate Change Initiative of Buchwitz et al. (2015). The temporal revisit time should be as frequent as possible, in order to detect short-term changes of emissions, and to deliver significantly smaller uncertainties on regional emission trends than currently achieved using bottom-up inventories.

Chapter-4 identifies critical issues and components for the operational processing of emissions by combining inventory and in-situ data with Earth-Observation data using the top-down atmospheric approach. It focuses on the need for the evolution ("deltas") from current capabilities, which are mainly research-based and oriented towards the determination of natural CO₂ fluxes from the ocean and land ecosystems, towards future operational long-term mission of emissions monitoring.

Chapter-5 proposes a realistic solution that is achievable with current technology, which involves building a space segment dedicated to the monitoring of fossil CO₂ from space, a complementary in-situ monitoring network focused on Europe, and an operational data-assimilation platform to deliver fossil CO₂ emission estimates. The notional cost of the space segment should remain commensurate with the current cost of a line of the Sentinel satellites within the Copernicus programme, with additional costs for modelling and in-situ data provision. A more detailed cost estimate will have to be carried out as part of a broader system engineering analysis, involving key stakeholders such as space agencies, inventory agencies and industry.

Chapter-6 highlights the three main phases towards implementation of a European space-borne observation capacity for CO₂ emission monitoring.

1. The bottom-up approach: CO₂ emissions from inventories

Current emission inventories are based on self-reported statistical data by the emitters themselves. Despite efforts to improve inventories, fossil CO₂ emissions information is becoming more uncertain due to different factors such as the growing importance of non-Annex I countries with more uncertain emissions data. Recognized limitations of inventories are:

- 1- They are difficult to independently verify since they require most of the available information to be compiled.
- 2- They are limited in scale, given the limited granularity of economic data.
- 3- They require considerable infrastructure and technical capacity, so that their quality is highly variable between countries.
- 4- While internationally accepted guidelines for reporting national emissions (of IPCC) exist the underlying economic information differs a lot between countries, leading to potentially biased emission estimates. Inter-comparability between inventories could only be independently obtained with an internationally accepted set of measurement data.

An observation system of fossil CO₂ emissions aiming to improve national inventories will need to have a typical accuracy on the order of few percent or better, for annual emissions of each country. Strong emission sources and sub-national patterns of emissions will need to be independently assessed within countries.

A fossil CO₂ emissions observation system should also have capabilities to quantify emissions trends over a period of few years in a transparent way, at the scale of countries, of regions within countries, and if possible of cities and emissions hotspots.

Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) (1992) was ready for signature two years after the first qualitative assessment report of the Intergovernmental Panel on Climate Change (IPCC) and entered into force, on March 21, 1994. The ultimate objective of the UNFCCC is to achieve “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”, (UN, 1992). The treaty adopts legally binding protocols for limiting the greenhouse gas emissions, such as the Kyoto Protocol (1999, in force in 2005). An essential component of the UNFCCC to achieve its objective is information on emissions of greenhouse gases. Its member states - 195 Parties as of August 2015- are classified as either Annex I countries (43) or non-Annex I countries (152). Annex I countries are most industrial countries, including (i) members of OECD24 in 1990 (except South Korea and Mexico) and (ii) other European countries and Russia (the countries with economies in transition (EIT)).

Annex I countries are required to submit annually complete inventories of anthropogenic greenhouse gas (GHG) sources and sinks. The inventories include emissions of CO₂, CH₄, N₂O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆). All annual inventories include a time series from the base year 1990 onwards, except those of some EIT countries with economic collapse in that period for which an earlier base year (1989) is accepted.

Non-Annex I countries submit their GHG inventories as part of their National Communications. To date 147 of the 152 non-Annex I parties have submitted their first National Communication, including a chapter with a summary of the GHG inventory. 94 Non-Annex I Parties have submitted their second National Communications, 14 their third one and one Non-Annex I country has submitted its fifth one. No specific documentation of inventory is required, and they are reviewed only briefly as part of the national communication review.

For the purpose of this report we focus on inventories of emissions of fossil carbon dioxide, the most important GHG. The greatest contribution to the increase in atmospheric CO₂ and observed climate change over the last 50 years comes from emissions from the combustion of fossil fuels and cement production. Therefore errors associated with these emission estimates (Ballantyne et al., 2015) may translate into ill-informed policy decisions about the necessary amount and country shares of future emission reductions.

While the carbon dioxide emissions are remaining approximately constant (within a few percent) over the 1990–2010 period, the global emissions that include contributions from non-Annex I countries exhibit a significant increase (Figure 1). The difference between the lowest and highest estimate of global carbon dioxide emissions ranges between 6.8 and 8.4 percent for the period 1990–2010 (UNEP, 2012) (Figure 1). The uncertainty associated with energy-related carbon dioxide emissions data is lowest among all greenhouse gases (UNEP, 2012). However, there are several important reservations concerning the accuracy of anthropogenic CO₂ emissions, that varies strongly between countries. The uncertainty of fossil CO₂ emission inventories of non-Annex I countries can be two to three times larger than that of Annex I inventories. It is obvious that with increasing share of non-Annex I inventories, the uncertainty on the global CO₂ total increases (Figure 2), despite all national efforts to increase the quality of the reported CO₂ inventory. Moreover, as we will document, the current emission information may not be fit-for-purpose in the near future, as shown in the next sections of this chapter.

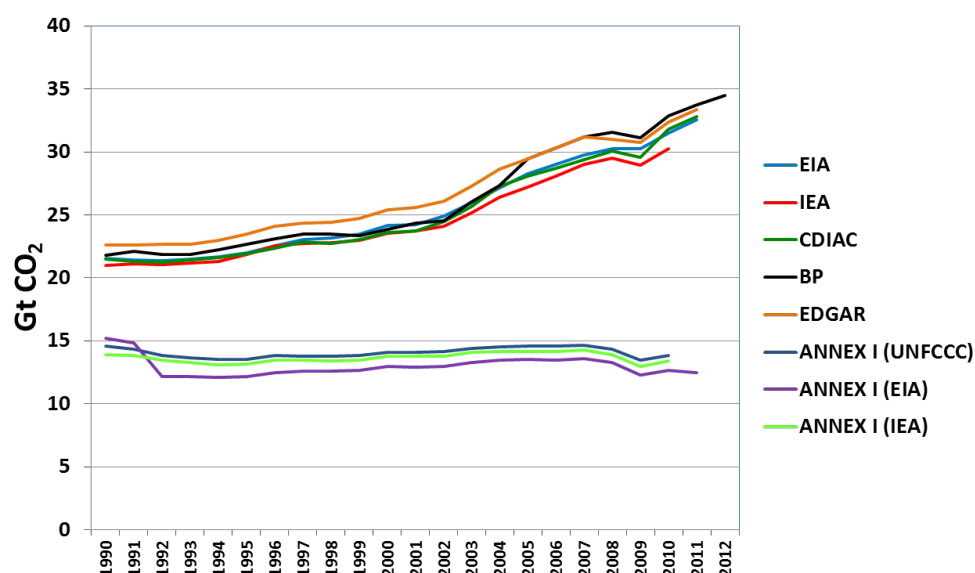


Figure 1. Global and developed countries (Annex I) carbon dioxide emissions from fossil-fuel use, by source of data. Sources: BP (2013); CDIAC (2013); EIA (2013); IEA (2012); JRC/PBL (2011) UNFCCC (2013). Units = Gt CO₂, i.e. billion tons of CO₂ (UNEP (2013) Appendix 2A. The Emissions Gap Report 2013. United Nations Environment Programme (UNEP), Nairobi. © UNEP 2013).

Emission model-based Inventories

Current inventory techniques are retrospective since they require gathering economic statistics on classes of activity. This implies that inventories are always at least 2 year behind present day and for many countries in the world often more. There is an increasing amount of real-time, operational data available, which can inform on emissions at many scales. For example, many jurisdictions publish energy-dispatch or continuous emissions data from power stations. Observations of night-time lights have been used to estimate the spatial structure of emissions while the increasing density and sophistication of traffic data allows estimates of transport emissions.

These emerging data streams are usually indirect proxies for anthropogenic emissions. It is proposed in [Chapter-2](#) to combine proxy data on emissions with satellite and in-situ atmospheric measurements. Indeed the two data-streams can be combined to use the spatial guidance given by the high-resolution proxy data (such as night-time lights) with the larger-scale constraint afforded by atmospheric measurements. The high-resolution information from the proxy measurements is important for interpreting the atmospheric data since incorrect small-scale information can bias even large-scale flux estimates.

Proxy information which can inform on emissions will likely increase in the future in both range and richness. Mobile phone connection data can already track real-time population movements while increasing use of vehicle telemetry will spread traffic information beyond current on-road monitoring. Finally demand-based pricing and demand management of the electricity system require high-frequency measurement of electricity use, already available in many jurisdictions. Innovative use of such data will provide increasing spatial richness in emissions estimates. This will allow both more rapid policy responses to changing patterns of energy use and, probably more importantly, be a tremendous tool for community engagement in the task of emissions reduction.

Differences between emission inventories

Global emissions of fossil CO₂ increased significantly during the last 5 decades, but relative errors of emissions have also increased (Ballantyne et al., 2012). Guidance on evaluation of emission uncertainties can be obtained from the evaluation of national inventories reported to UNFCCC (Jonas et al. (2010) and references therein). Andres et al. (2012) and Marland et al. (2009) grouped countries based on the accuracy of their statistical infrastructure. Countries with well-maintained statistical infrastructure are the OECD-1990 countries plus India, for which an uncertainty of 3% to 5% was estimated. Other countries show a larger range of uncertainty of 10% (Gregg et al., 2008; Tu, 2011; Olivier, 2002).

Deficiencies in current CO₂ emission inventories for UNFCCC

Annex I versus non-Annex I country inventories

Although existing greenhouse gas inventory requirements for Annex I countries appear adequate for measurable, reportable and verifiable mitigation commitments, such a system is not yet in place in non-Annex I countries. At the time the UNFCCC was drafted, it was noted that “the largest share of historical and current global emissions of greenhouse gases has originated in developed countries”. Since then, the situation has reversed: emissions from Non-Annex I countries have surpassed those of Annex I countries in 2004, and this trend continues in 2013 with 60% of the global CO₂ emissions coming from non-Annex I countries (Figure 2). This trend creates a paradox; while for each individual country (both Annex I and non-Annex I) the quality of the inventory is stable and/or improves over time, the uncertainty of all country emissions together is growing because of less accurate emissions of non-Annex-I countries (Marland et al., 2009). The growing uncertainty is a logical consequence of the trend shown in Fig. 2.

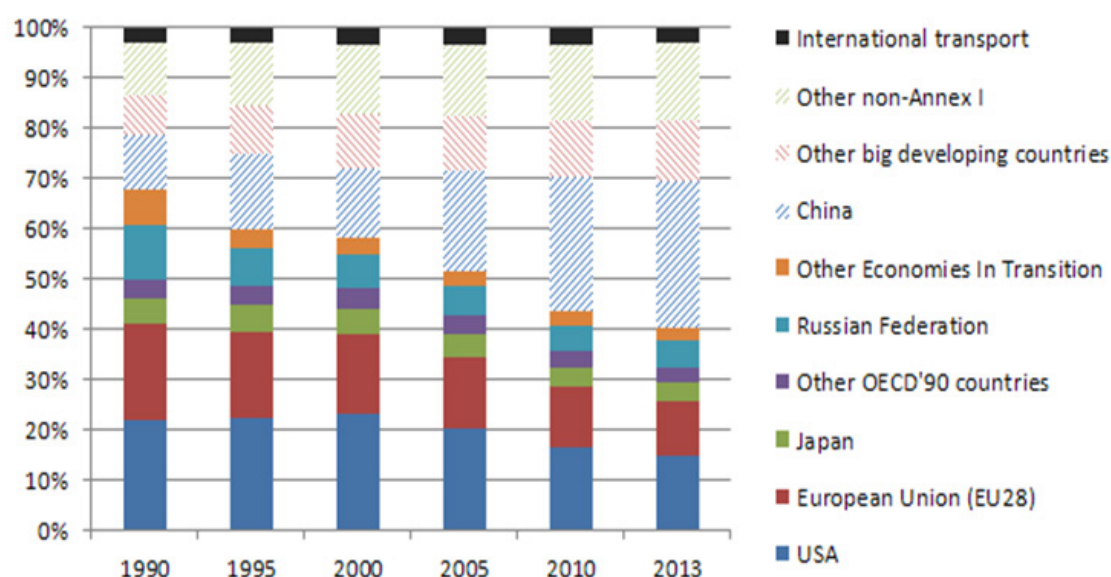


Figure 2. Relative contributions of different groups of countries to global fossil CO₂ emission. The hatched stacks represent non-Annex I countries (Graph based on data from EDGAR v4.3 (EC-JRC/PBL, 2015) and Olivier et al. (2014). The period is from 1990 to 2013.

In line with this observation, Liu et al. (2015) reported a substantial revision of the Chinese annual global carbon emissions, reducing the global emissions in 2013 by 0.35 GtC, an amount larger than the reported increase in global emissions between 2012 and 2013. The major difference between Liu et al. (2015) and the previous estimate seems to derive from the coal carbon content, a parameter that is country-dependent and not known accurately for each world country. Moreover, the National Bureau of Statistics of China announced that the 2013 coal production figure will be revised upward by up to 7-8%, which was not taken into account in Liu et al. (2015). Revisions by 10% of the emissions of the World largest emitter (China) from one year to the next, are illustrative of systematic errors for non-Annex-I countries.

Dialectics of lead

The UNFCCC in combination with the IPCC tiered methodology and IPCC Guidebooks on emission factors has created an easy-to-use system for estimating national CO₂ emissions. This has been a success story, and in the 1990s countries were very active in further improving and generating more detailed methodologies. Many countries have, however, realized that more detailed methodologies, which deviate from IPCC methodology, are labor intensive, demanding in maintenance and reporting requirements, and therefore costly. Moreover a change in methodology provides a discontinuity in the time-series and calculations backwards in time are needed for any trends analysis.

In the light of transparency but also from a cost perspective it may look more attractive to stick with a clear IPCC methodology. While this facilitates comparison, it might not be optimal in terms of knowing what the true value of emissions really is. Sometimes better methodologies than IPCC are known but costly to repeat on an annual basis. Also given the fact that IPCC demands, rightly so, that deviations from IPCC methodology are rigorously documented and published. This may increase the difference between IPCC compliant emission reports and real world emissions.

International transport emissions

Some emission sources are only partially addressed by the countries. This is the case for the international transport emissions. The activity data to estimate these emissions are generally known as international bunker fuel statistics. IMO (2014) demonstrated the relative large differences in estimates for international shipping emissions globally. International transport emissions can only be properly assessed and monitored by a combined global initiative and the inclusion of responsible organizations in the list of parties/observers to UNFCCC. Current inventories for international transport emissions are too uncertain, lack a yearly reporting cycle and have difficulties showing for example the success of energy efficiency improvements due to economy of scale (e.g., bigger ships) or penetration of better engine technologies because there is no coupling between these activity data and bunker fuels statistics.

Oil and gas sector emissions

Some of the CO₂ emissions related to the oil and gas industry are highly uncertain as they may partly escape the high quality fuel use statistics. Examples are flaring, burning of oil and/or gas fields due to wars or accidents and coal mine fires. For example, for flaring EDGAR reports values about twice as high as CDIAC and EIA. This difference can be explained by the different estimation method for the activity data, which is mainly based on reported energy statistics for CDIAC and EIA but mainly on satellite data for EDGAR. Also Stohl et al. (2013) reported substantially higher emissions from flaring than previously accounted for. Such sources that partly escape the statistics are highly uncertain and poorly represented in self-reported country data.

Global spatial and temporal distribution of fossil CO₂ emissions

The self-reporting of CO₂ emissions by countries to UNFCCC does not include spatial details of emissions within the country. Nor does it include timing of emissions throughout the year. For modelling and understanding the dynamics of CO₂ emissions, spatial and temporal disaggregation is necessary. One of the main suppliers of spatially disaggregated CO₂ emissions data is the Emission Database for Global Atmospheric Research (EDGAR) of EC-JRC/PBL (2011). EDGAR provides bottom-up estimates of the global anthropogenic emissions based on publicly available statistics and provides consistently distributed 0.1deg x 0.1deg emission maps, but there is no update after year 2010. The Peking University combustion CO₂ inventory (PKU-CO₂) of Wang et al. (2013) provides fossil CO₂ emission gridded data with the same resolution and global coverage, but only for year 2007. PKU-CO₂ includes an uncertainty assessment based on Monte-Carlo simulations. Wang et al. (2013) concluded that the spatial distortion of CO₂ emissions by using a nationally disaggregation method could be significantly reduced by using sub-national fuel data, in particular in large countries with uneven regional economic development.

Point sources (power plants, steel plants, refineries etc.) are key sources of CO₂, representing hotspots in the emission grids, but their strengths and locations are subject to input errors with large consequences and cannot be extrapolated in time. For example, the closure of power plants – typically located at river banks or coasts that are also country borders – can change the emission distribution pattern from one year to another. Closure can be temporarily: during the economic crisis several (large) power plants went into hibernation to be started again when demand rose. Line sources are typically used for the transportation activities but when the exact location is not well-known, representative proxies, mostly of diffusive type are used, sometimes suggesting more accuracy than present in reality. Another source of uncertainty in gridded emissions data are country border cells. Earth Observation data could help improve the spatial distribution of emissions, by identifying the large point sources and their emissions variation over time (e.g., Schneising et al., 2013, 2014; Reuter et al., 2014a; Fioletov et al., 2013; 2015; Denier van der Gon et al., 2013).

It has also been demonstrated recently that images of CO₂ or CH₄ plumes from remote sensing airborne measurements can be inverted to yield the emissions of power plant (Krings et al. 2011) or coal mine ventilation shafts (Krings et al. 2013).

Downscaling of national emission inventories to sub-national or city level

In general there are severe problems to reliably scale down emission distributions from the national scale to the subnational or city scale because the activity data used in national reporting are often not available at smaller scale. The best maps of emissions are those derived from local representative data, covering a specific area, such as the VULCAN fossil fuel CO₂ emissions maps of Gurney et al. (2009). Where these are not available, alternative proxies like population density or traffic intensity are used but uncertainty remains substantial. Comparisons between downscaled national emission inventories and city scale bottom-up inventories revealed large discrepancies (Denier van der Gon et al., 2011; Zhu et al., 2012). While these studies mostly looked at air pollutants, a similar uncertainty exists for CO₂. For example, a proxy to downscale residential combustion emissions is population density. It is known, however, that heating in cities profits from economy of scale – it takes less energy per person to heat an apartment block than a rural country house. Currently there is a quickly growing demand for city scale emission inventories as cities have clear voluntary ambitions to play a bigger role in abating climate change (e.g., C-40 Cities Leadership Group, Covenant of Mayors, US Conference of Mayors, Local Government (ICLEI), Global Compact of Mayors). However, global, reliable city scale emission inventories do not exist at present, nor do cities have the means in place to monitor their progress towards carbon reduction objectives. At city level, no binding agreements applies and most actions are voluntary (subsidiarity principle). Therefore many city inventories are not accounting all emissions that take place on the city's territory but restrict the accounting to those sectors under their governance or those with reduction measures.

Need for independent data to assess the accuracy of emission inventories

There is a high demand for independent verification of trends in national CO₂ emissions over 5-10 year time frames and longer. Do countries achieve what they promise? Is the “proof” acceptable to all parties? Den Elzen et al. (2013) analysed how the accounting method influences the final inventory and showed that this is not always in accordance with the historic responsibility. Moreover, the international review of country reports cannot fully harmonise all the inventories. An international independent way of estimating emission changes for all world countries based on internationally accepted data (e.g., satellite data with good spatial coverage) would create a level playing field and an independent basis for further reductions, whether voluntary or not. The option of using “top-down” atmospheric measurements to verify the quality of emission inventories is not yet deployed by the governments, even though some countries (UK, Ireland) include a consistency check with atmospheric measurements in their reports to UNFCCC. Atmospheric top-down inverse modelling (Chapter-2) using emission inventories as prior information, satellite and ground-based data should allow assessment, evaluation (and improvement) of the emission inventories, and, over time, monitoring the effectiveness of emission reduction measures in the context of national commitments and subnational voluntary efforts.

2. The top-down atmospheric approach to improve emissions inventories

In order to provide independent estimates of fossil CO₂ emissions using atmospheric measurements and inversion modeling, increasing the density and spatial resolution of atmospheric CO₂ measurements is needed, since emissions are highly concentrated over small areas. We recommend the development of two complementary lines of approach:

- 1- Focus on the dense sampling of selected emissions hotspots, such as megacities and major industrial areas, large power plants. These hotspots are typically reflected by atmospheric CO₂ plumes, which could be mapped from space with instruments that have high-resolution sampling. Emissions from hotspots could additionally be monitored with urban CO₂ in-situ networks.
- 2- Separate the fossil CO₂ component from the natural CO₂ fluxes at regional scale, by measurements of additional trace species, such as radiocarbon (¹⁴C in CO₂) and carbon monoxide.

The inversion of fossil CO₂ emissions using atmospheric data will require not only a high density of observations, especially over hotspots, but also a very good representation of regional atmospheric transport processes in atmospheric models, and a more detailed provision of gridded emissions data to be used as a priori information for inversions.

The approach we recommend to develop is a Fossil Fuel Data Assimilation System (FFDAS) that will combine atmospheric observations with other data-streams such as emission information and proxy data, and will provide optimized emissions maps with their uncertainty.

Introduction

While bottom-up inventories provide detailed and –to some extent – traceable information on CO₂ emissions, they have some shortcomings, summarized in [Chapter-1](#). This calls for a technique to refine and/or independently evaluate emissions inventories. So-called “top-down” methodology, based on atmospheric CO₂ measurements together with a model of atmospheric transport in principle provides an approach to do both.

The top-down (or inversion) approach (Figure 3) makes use of the fact that sources and sinks of atmospheric CO₂ are reflected in the atmosphere by spatio-temporal variations of the atmospheric CO₂ concentration. Measurements of atmospheric CO₂ can thus be used to quantify sources and sinks at the earth surface. This has to be done with the help of a numerical atmospheric transport model, which relates the surface fluxes to the atmospheric concentrations at the observation space-time location. Such a model solves numerically the continuity equation for an atmospheric constituent (e.g., a trace gas such as CO₂) given the three-dimensional, time-varying meteorological fields describing the state of the atmosphere. These are either obtained from analyses of numerical weather forecast models or from atmospheric general circulation models running in climate mode.

Currently employed global atmospheric transport models have horizontal resolutions of 2°-5° latitude and longitude and up to 50 layers in the vertical dimension.

In order to represent a particular region more closely, a nested higher resolution grid or a non-uniform zoom region may be employed. Ultimately the resolution of atmospheric transport models is limited by the resolution of the available meteorological fields. The most highly resolved meteorological fields are typical at 1 km, but over limited domains. This holds also for the temporal resolution, which is currently of 3-6 hours as determined by the availability of the meteorological analyses. Obtaining finer temporal resolutions for meteorological analyses is easily achievable, if needed.

The estimation of CO₂ sources and sinks from atmospheric measurements is a mathematically ill-conditioned inversion problem. It is also an underdetermined, because neither the present in situ observation network, nor any current space borne observation system is dense enough to fully resolve the complexity of CO₂ sources and sinks as existing in nature. Inverse techniques are a branch of Bayesian statistical inference⁴. They combine three ingredients: (1) prior knowledge with (2) observations and (3) atmospheric transport models, to infer information (e.g., magnitude and error estimates) of the desired quantities, such as surface-atmosphere CO₂ fluxes. This information is expressed by probability distributions (PDFs). The underlying assumption is that the true state of the system is consistent with the prior knowledge, measurements and the model, which relates the two. Crucially the methodology allows not only a refinement of prior knowledge but also a rigorous evaluation of the consistency of the three sources of information. The prior knowledge may be obtained from flux field estimates derived with bottom-up methods, existing inventories (in particular of the CO₂ from fossil fuel burning), statistical information (e.g., assuming that certain sources are correlated within a given spatial and/or temporal domain), and it may be specified based on ad hoc plausibility arguments (e.g., no CO₂ sources over ice sheets or deserts).

Atmospheric inverse methods have provided much of the information on the large-scale carbon cycle such as the existence of a northern terrestrial sink (Tans et al., 1990) or the role of the tropical land in modulating interannual variability (Bousquet et al., 2000). Recent advances in modelling and measurement mean that such information is now available at much smaller scales. Firstly Law et al. (2002) noted that high-frequency variations in concentration reflected smaller scale features in emissions. Next improvements in high-resolution modelling meant that such features could be simulated with enough accuracy to allow source recovery (Geels et al., 2007; Sarrazat et al., 2007). This allowed the recovery of sources first over smaller agricultural regions (Lauvaux et al., 2009; Schuh et al., 2013) or urban scales (Bréon et al., 2015).

Recent development involves solving not directly for the spatio-temporal distribution of surface fluxes, but optimizing a surface flux model with unknown parameters (Kaminski et al., 2002, Rayner et al., 2005). The parameters of the combined surface flux - atmospheric transport model are then determined by minimizing the mismatch between the simulated and observed concentrations. With this approach the inversion problem becomes non-linear, and, depending on the complexity of the surface flux model, computationally expensive. On the other hand, this approach typically reduces the number of unknowns and thus regularizes the inversion problem, essentially using prior process information as represented in the surface flux model. This parameter optimization approach is often termed “Carbon Cycle Data Assimilation” (CCDAS, Rayner et al., 2005).

⁴Tarantola (1982) gives a good overall introduction to the methods while Enting (2002) or Ciais et al. (2010a) describe their application to atmospheric inverse problems.

Constraining fossil CO₂ emissions using top-down inversions

When addressing CO₂ budgets at regional scale such as over Europe, two main contributions have to be considered: (1) CO₂ emissions from fossil fuel burning and cement production and (2) CO₂ exchange fluxes with natural systems, i.e. terrestrial ecosystems (forests, grasslands, pasture, agriculture, wetlands etc.) and the ocean waters within the considered region, also including exchanges with freshwaters (lakes, rivers) and coastal waters.

In practice the fluxes of (2) often overwhelm (1) during summer season when the CO₂ uptake by the vegetation is the strongest. However, at the annual mean, in populated regions, emissions (1) dominate over natural fluxes (2).

Traditionally, atmospheric inversions have been developed for carbon cycle research with the goal of quantifying (2) at large scales, while prescribing fossil CO₂ emissions from bottom up inventories as being well known.

The paradigm of “well known emissions” does not hold any longer (see [Chapter-1](#)) and we thus propose to apply the top-down inversion approach to constrain for fossil CO₂ emissions using atmospheric data. An inversion system with capabilities to resolve fossil CO₂ emissions will combine emission inventories data (or an emission model in the case of a Fossil Fuel Data Assimilation System (FFDAS) as prior, as well as prior knowledge of natural fluxes, with specific top-down atmospheric CO₂ measurements allowing to separate emissions from natural fluxes (see [Chapter-3](#) and [Chapter-4](#)).

The main products of such a top-down atmospheric inversions will be improved maps of fossil CO₂ emissions (optimal emission estimates) with temporal variability and associated uncertainties. These emission estimates will be fully consistent with independent atmospheric CO₂ observations⁵.

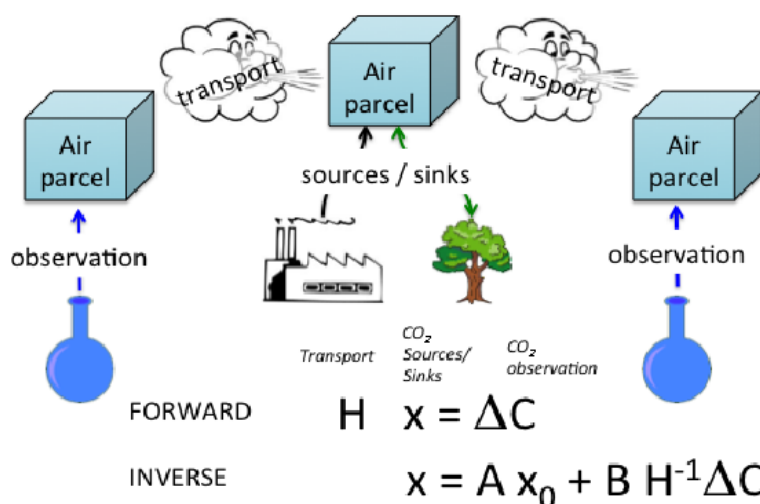


Figure 3. Scheme illustrating the principles of atmospheric tracer inversions. In the forward sense an atmospheric tracer transport model (described by the operator H) links surface fluxes (sources/ sinks, x in the figure) to concentration gradients (ΔC) between two locations (samples), for instance two satellite soundings, or two ground-based stations. The inverse calculation is more complicated because of the underdetermined nature of the problem (as detailed in the text). An optimal field of x is obtained by combining information from a prior estimate x_0 and the observed concentration gradient fed back through atmospheric transport. Weights A and B depend on the relative confidence in the two sources of data. In the illustration, the plant is a “source” i.e. it emits CO₂ to the atmosphere and the tree is a “sink”, i.e. it removes CO₂ from the atmosphere. During the growing season, ecosystems absorb CO₂, but they emit it during the non-growing season. The combustion of fossil fuels and cement production always emits CO₂ to the atmosphere.

⁵ A valuable by-product will also be optimized natural CO₂ fluxes, since this component will be separated from the emissions in the inversion process.

Improving inventory models using data assimilation

A variant of the above mentioned carbon cycle data assimilation systems aims at specifically optimizing the parameters of an emission inventory model (as mentioned in [Chapter-1](#)), and thereby to produce optimized fossil CO₂ emissions maps based on a small number of controlling parameters.

This approach is called Fossil Fuel Data Assimilation System or FFDAS. The principle of FFDAS is to assimilate national statistics on fossil fuel CO₂ consumption and other census data together with atmospheric CO₂ and tracer measurements into an emission model ([Chapter-1](#)) to improve its parameters and provide optimized emission estimates including uncertainties consistent with the ingested data.

Current limitations of inversions

A number of important limitations with the state of the art of atmospheric inversions based on the current in-situ observation network should be listed:

- Current atmospheric transport models, in particular the numerical representation of sub-grid scale mixing (e.g., surface and planetary boundary layer dynamics, vertical transport in convective clouds) is far from perfect. A robust fossil fuel CO₂ emission observation system will thus require higher resolution transport models, rigorously tested against transport tracer data, and with improved model transport parametrisations (e.g., boundary layer dynamics and vertical transport).
- The current in situ observational network is very sparse, i.e. there exist only a few 100 monitoring stations worldwide. Furthermore, at some stations the sampling frequency is low, and there are often gaps in the observations. The current in-situ network was not designed to measure fossil CO₂ emissions but rather large-scale natural fluxes. A needed evolution of in-situ networks towards the capability to discriminate fossil CO₂ emissions from surrounding natural CO₂ fluxes is proposed in [Chapter-4](#).
- Individual measurements are often not representative of the appropriate temporal and spatial scale of the transport model. One way to overcome this limitation is to use global high-resolution models, ideally at the same horizontal scale (few km) as the satellite data they will assimilate.
- Individual concentration observations are of limited accuracy and precision, and observations from different satellites, or in-situ networks, are often not easily comparable, because of differences in measurement techniques and uses of different standards. This is most important when assessing changes in long-term trends in sources, which are reflected in second derivatives in the atmospheric concentration trends, whose detection is highly sensitive to errors in measurements. This limitation can be overcome through frequent inter-comparison, calibration and quality control activities.
- Current atmospheric measurements do not allow to discriminate localized fossil CO₂ emissions from surrounding biogenic CO₂ fluxes, with a high spatial and temporal resolution.

As an example [Figure 4](#) shows three snapshots from a high-resolution (2 km) simulation of the column averaged CO₂ concentration (expressed as an anomaly of the mean value) over Europe. The three scenes are taken at 13:00 UTC on three different days. The March 23rd and April 1st images represent typical conditions when the land biosphere fluxes are rather small, and the fossil fuel signal is clearly visible as red anomalies. The zoom over Central Europe shows the plumes from large cities (white) and power plants (black).

The May 3rd image represents spring conditions when the land biosphere acts already as a strong sink during the day. During that day, a negative concentration anomaly develops during the day over Western Europe (blue), which overwhelms the fossil CO₂ source signatures in that region. Individual plumes from localized fossil CO₂ emissions are still visible in the first scene over Germany and Poland. The strong contrast between the three scenes, taken few days apart, illustrates further the dominant control of atmospheric mixing and transport.

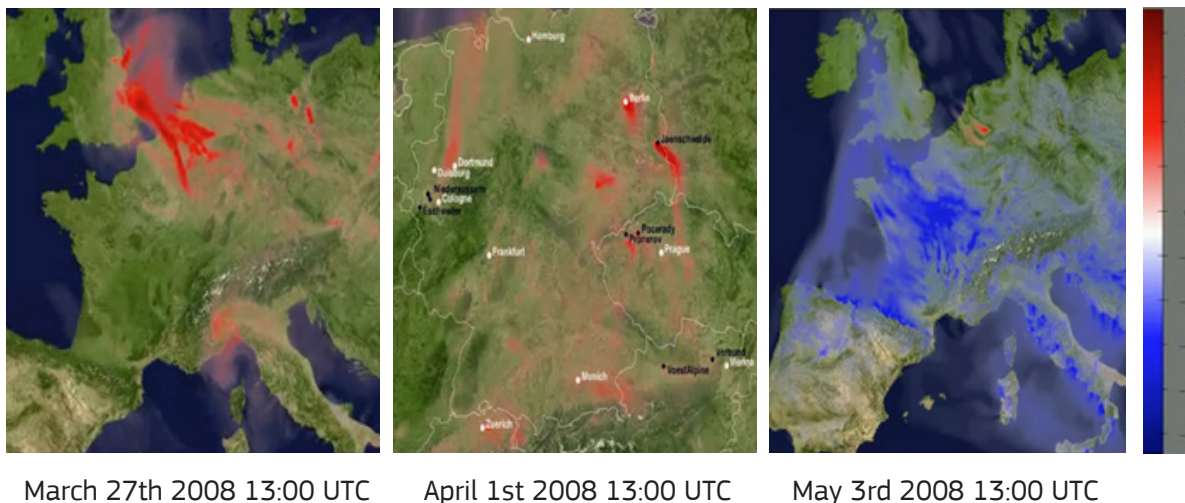


Figure 4. High-resolution simulation of column-averaged CO₂ concentration (analogous to would be observed by satellites) over Western Europe (left and right) on zoomed over Central Europe (middle) during two consecutive days in 2008. Units are ppm XCO₂ and fields are expressed as anomalies from the mean in the domain. Simulations performed with the COSMO high-resolution atmospheric transport model of Empa prescribed with fossil CO₂ emissions from EDGAR and biogenic emissions from the VPRM vegetation model (Courtesy of D. Brummer, Empa).

The abovementioned limitations can be overcome by collecting two types of atmospheric measurements:

- Dense atmospheric CO₂ measurements, with detailed, high resolution, coverage of emissions hotspots. With their global and high revisit coverage, satellite observations of column integrated CO₂ (XCO₂) at high spatial resolution can meet this requirement, e.g., using space-borne sensors with imaging capabilities ([Chapter-3](#)).
- In-situ measurements of specific tracers in the atmosphere that allow the separation of fossil CO₂ from other sources. The best of these tracers is ¹⁴C (radiocarbon) in atmospheric CO₂, which is nearly a direct tracer of emissions (Turnbull et al., 2014) but is so far expensive to measure because of its very low abundance. Fossil fuels do not contain any radiocarbon: when CO₂ from their combustion is released to the atmosphere, it dilutes with CO₂ from other sources that contain ¹⁴C, which creates a measurable depletion of the ¹⁴C isotope composition in air masses containing fossil CO₂. The accuracy at which the fossil fuel component of atmospheric CO₂ can be determined from ¹⁴C measurements of CO₂ in air samples is about 1 ppm with Accelerator Mass Spectrometry. Carbon monoxide is also a tracer of combustion processes. In many environments, it is a reasonable tracer of fossil fuel emissions (Gammitzer et al., 2006) though subject to uncertainty in emission ratios of the two trace gases (CO₂ and CO) caused by differences in fuel type and combustion efficiency.

3. Space based greenhouse gas measurement capabilities and future missions

Specific measurements of atmospheric CO₂ from space are needed for improving fossil CO₂ emissions estimates.

Over the next decade, a succession of partially overlapping missions with a range of CO₂ and CH₄ measurement capabilities will be deployed in low Earth orbit. Each mission has been conceived with unique capabilities, designed to improve the measurement precision and accuracy, as well as the spatial and temporal resolution, and coverage to improve understanding of surface fluxes of GHG from the continental to local scales. Europe was an early pioneer in this area, with SCIAMACHY, and will continue to have a significant contribution to the observation of natural fluxes with future missions planned or under development, such as MICROCARB and MERLIN.

Current missions are not designed to quantify emissions but natural fluxes. Exceptions being OCO-3, designed to take XCO₂ repeated images over selected hot-spots, and CarbonSat that was designed to take images of XCO₂ (and XCH₄) with 250 km swath, for quantifying emissions when the satellite passes over hotspots:

- 1- In the near term, before 2025, a carbon mission delivering XCO₂ with high resolution (typical pixel size of less than ≈ 3 km in size), imaging capabilities, precision of ≈ 1 ppm for individual XCO₂ measurements with systematic errors < 0.5 ppm, and global coverage, is of strategic importance for Europe to acquire the capacity of quantifying fossil CO₂ emissions.
- 2- In the long term (by 2030) a set of (European and non-European) carbon missions with similar or better capabilities will be required for the frequent detection, quantification and monitoring of emissions. We recommend in this context the consideration of combined active and passive space-borne sensors. Such a closely coordinated space-based combination of sensors would also provide continuity and resiliency to losses of data from individual satellites.

For those periods when more than one mission is returning data, much greater benefits could be realized if space-based measurements could be coordinated with each other and with the surface in-situ monitoring network, to produce a global monitoring system with the resolution and coverage needed to provide policy-relevant information. To meet this objective, the measurements will need to be calibrated against internationally recognized standards.

Background

Measurements from the ground based greenhouse gas network accurately track the global atmospheric CO₂ budgets and their trends, but do not have the resolution or coverage needed to identify the regional magnitude of sources emitting these gases into the atmosphere or the natural sinks that absorb or destroy them. This information is critical to any carbon management strategy.

One way to improve the spatial and temporal coverage and resolution is to retrieve precise, spatially-resolved, global measurements of CO₂, CH₄, and other greenhouse gases from space-based platforms. High precision is essential in this application because surface sources and sinks produce their largest perturbations in CO₂ and CH₄ near the surface and these signals decay rapidly with height. For example, rapidly growing crops can absorb enough CO₂ to change its atmospheric mixing ratios by up to 8% (>30 ppm) in the planetary boundary layer, and strong industrial emission sources can produce even larger local increases in this gas. However, the corresponding XCO₂ variations for fossil CO₂ emissions rarely exceed 2% (8 ppm), and are typically no larger than 0.5% (~ 2 ppm) on scales that range from ~100 km over continents to 1,000 km over the ocean (Miller et al., 2007). High accuracy is thus particularly critical for unbiased emission estimates using atmospheric inversions⁶.

Thermal infrared sensors, such as the Atmospheric Infrared Spectrometer (AIRS) (<http://airs.jpl.nasa.gov/>), the Tropospheric Emission Spectrometer (TES) (Kulawik et al., 2010), and the Infrared Atmospheric Sounding Interferometer (IASI) (EUMETSAT, 2015), collect both daytime and nighttime measurements of CO₂ and CH₄. However, these measurements are most sensitive to the distribution of these gases in the middle to upper troposphere, and are much less sensitive to their variations near the Earth's surface, where surface sources and sinks produce their strongest signatures of emissions and uptake. The Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) measures limb solar occultation profiles of CO₂ and CH₄ spanning the upper troposphere and stratosphere, but also lacks the capability to measure variations in these gases near the surface.

Active measurement (LIDAR) systems, such as the MERLIN (for CH₄) and the planned ASCENDS missions discussed later in this chapter, could provide significant extra value to a set of passive systems. LIDAR systems operate at night, so coverage of high latitude zones and during the winter is enhanced. Cloud screening is less of a problem because of the narrow beam. Some vertical information can be extracted by the 'cloud slicing' technique, whereby signal returns from cloud decks and the surface can be compared, and the mixing ratio of the target gas in say, the planetary boundary layer, derived as a residual. Lastly, LIDAR systems exhibit low bias, and thus may be valuable for correcting passive retrievals. The main disadvantage of active systems is the lack of spatial coverage, so an optimal strategy might be to fly an active and passive system together on to realize the benefits of both systems. Such a combined active-passive set-up could be used as a calibration standard for the constellation of passive sensors currently in orbit and planned for the future.

High resolution spectroscopic observations of the absorption of reflected sunlight by CO₂ and CH₄ bands at near infrared wavelengths are better suited for monitoring surface CO₂ and CH₄ fluxes because these measurements can be analyzed to yield surface-weighted estimates of the column-averaged dry air mole fractions of CO₂ and CH₄ (XCO₂ and XCH₄). This is still a very challenging space-based remote sensing measurement. The pioneering sensors SCIAMACHY on ENVISAT, TANSO-FTS on GOSAT, and Orbiting Carbon Observatory-2 (OCO-2) were the first three instruments designed to exploit this approach. These three sensors are described below, along with a series of future instruments for measuring XCO₂ and XCH₄.

Past Greenhouse Gas Monitoring Missions

SCIAMACHY on ENVISAT (2002 to 2012): The SCanning Imaging Absorption spectroMeter for Atmospheric CartographY (SCIAMACHY) (ESA Earth online, 2015) provided a decade of global measurements of key trace gases in the troposphere and stratosphere from ENVISAT, which operated from 2002-2012 (Burrows et al., 1995).

⁶ Note that the requirements for detecting CH₄ sources are just as demanding, where a precision of 0.25% to 0.5% is needed to resolve typical (5 and 10 ppb) regional scale variations in XCH₄.

Measurements collected within the shortwave infrared (SWIR) CO_2 bands near 1580 and 1610 nm and the CH_4 band around 1600 nm were combined with spectra of the near-infrared (NIR) molecular oxygen (O_2) A-band at 765 nm to estimate XCO_2 and XCH_4 , respectively, providing the first, space-based global maps of these quantities (Buchwitz et al., 2015a). The latitudinal dependence of the XCO_2 and XCH_4 for SCIAMACHY from 2003 to 2012 is shown in Figure 4. The hemispheric gradient and the growth of the atmospheric loading are both clearly identified.

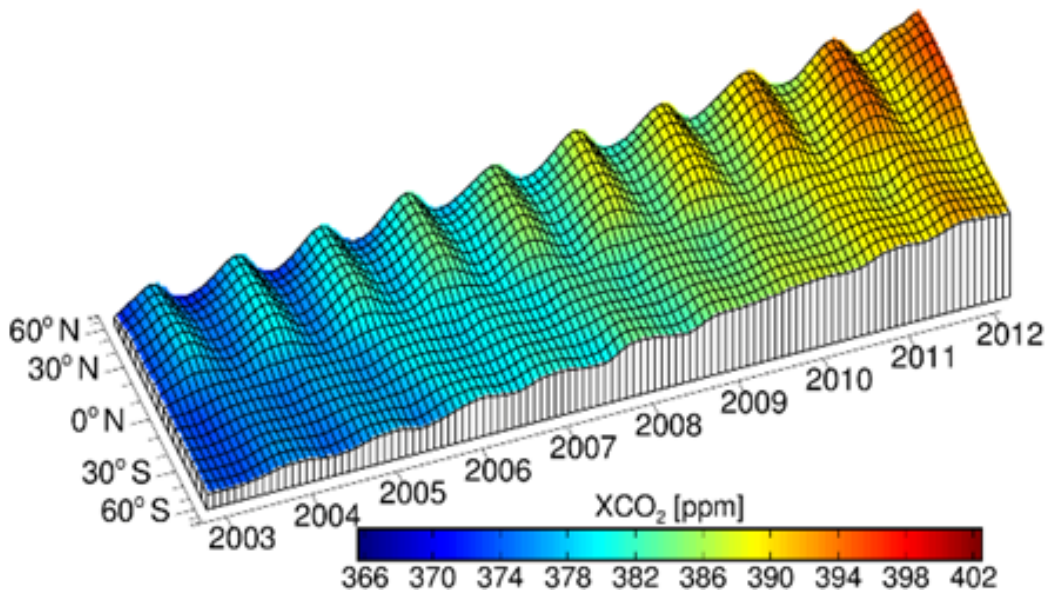


Figure 5. The time dependent, latitudinal zonal average XCO_2 retrieved from SCIAMACHY retrieval of (courtesy of Institute of Environmental Physics, University of Bremen). (Buchwitz et al, 2015a)

With its broad (1000-km) swath, SCIAMACHY provided very good coverage. However, its relatively low single-sounding precision (2–5 ppm) and large surface footprint (30 km by 60 km) limited its sensitivity to very intense sources of CO_2 and CH_4 emissions. This large footprint also increased the probability of contamination by clouds in partially cloudy regions, which introduce uncertainties in the optical path lengths, and must be screened out in the retrieval process. These factors limited the full science impact of the SCIAMACHY CO_2 and CH_4 measurements but nevertheless, SCIAMACHY pioneered important research areas, including the detection of signatures of anthropogenic CO_2 emissions (Schneising et al. 2013, Reuter et al. 2014a), an initial attempt to quantify the European carbon sink using space based data (Reuter et al. 2014b), as well as the detection and initial quantification of fugitive CH_4 emissions of large emission hot spots in multi-year data averages (Scheising et al. 2014, Kort et al. 2014).

Present Greenhouse Gas Missions

TANSO-FTS on GOSAT (2009 to present): The TANSO-FTS is a double pendulum interferometer that records reflected sunlight in molecular oxygen (O_2) A-band at 765 nm (13020 cm^{-1}), the CO_2 bands near 1600 nm (6250 cm^{-1}) and 2060 nm (4850 cm^{-1}), and the CH_4 band near 1670 nm (5990 cm^{-1}). It collects interferograms at 4-second intervals with a footprints of about 10.5 km in diameter at nadir. Since August 2010, observations over land are collected on a 3-point grid pattern, with footprints that are separated by about 260 km cross-track and about 280 km along-track. Over the ocean, the pointing mechanism directs the TANSO-FTS field of view to the bright “glint” spot to ensure adequate signal for CO_2 and CH_4 retrievals.

At other latitudes, a 5- or 3-point grid pattern is used. This approach yields about 10,000 soundings over the sunlit hemisphere of the Earth each day. Between 5 and 10% of these soundings are sufficiently cloud-free and have adequate signal to yield reliable XCO_2 estimates. The typical coverage provided by GOSAT is shown in in Figure 6.

As with SCIAMACHY, parallel efforts by multiple teams working on independent CO_2 and CH_4 retrievals from GOSAT observations have contributed to an intensive exchange of ideas and

methods among the teams, which has advanced retrieval performance. We refer to Yoshida et al. (2011), Butz et al. (2011), Crisp et al. (2012) and to the ESA Greenhouse Gas Climate Change Initiative (www.esa-ghg-cci.org). Comparisons of GOSAT TANSO-FTS XCO₂ retrievals with surface-based XCO₂ estimates from the Total Carbon Column Observing Network (TCCON) have helped to identify and correct subtle biases associated with air mass, surface pressure, optically-thick aerosols, ice-covered surfaces, and other environmental factors. Persistent spectral residuals common to TCCON and TANSO-FTS retrievals have revealed limitations in the spectroscopy of CO₂ and O₂, which are being addressed with new laboratory measurements. These calibration, retrieval algorithm development, and validation activities are now yielding XCO₂ estimates with regional-scale errors < 2 ppm over much of the globe.

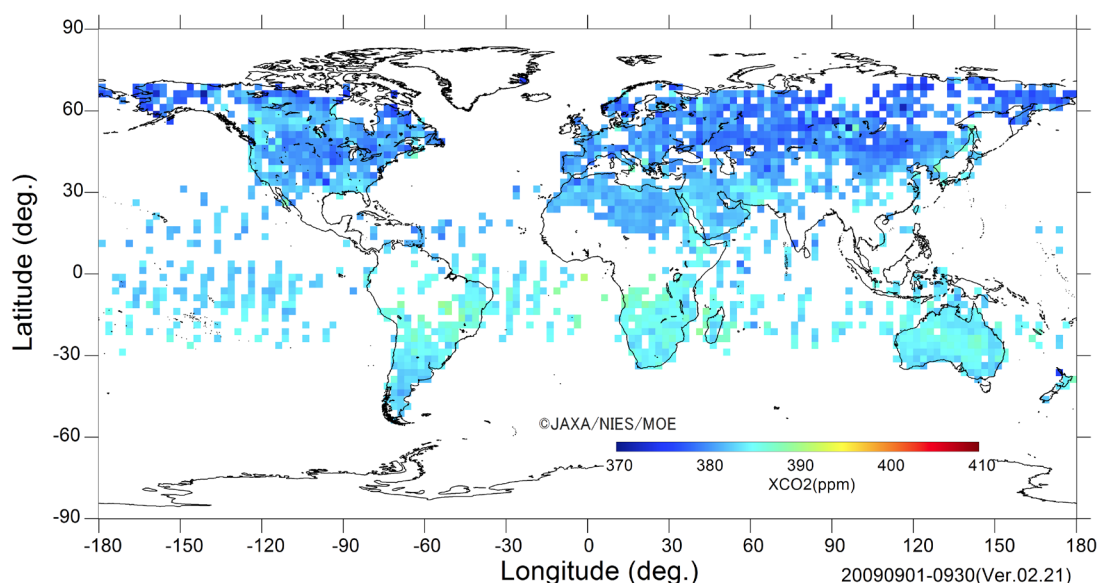


Figure 6. XCO₂ observations for one month (September 2009) from GOSAT TANSO-FTS, illustrating the extent of its nadir and glint coverage (FTS SWIR Level 2 XCO₂) (V02.21,V02.31,V02.40; T. Yokota (NIES), personal communication, 2015).

Although GOSAT CO₂ observations will help to constrain CO₂ fluxes from the biosphere and oceans on regional scales, its spatial sampling pattern is not optimized for monitoring emission plumes of large fossil fuel point sources, and its sensitivity is not adequate to detect typical CO₂ enhancements produced by the emissions of a large power plant, even when it is located within its 10.5 km diameter (~85 km²) surface footprint. Higher sensitivity (signal-to-noise-ratio), a smaller surface footprint, and denser sampling are needed to detect and quantify these signals.

OCO-2 (2014 to present): The NASA Orbiting Carbon Observatory – 2 (OCO-2) was successfully launched from Vandenberg Air Force Base in California on 2 July 2014. In early August, it was inserted at the head of the 705 km Afternoon Constellation (A-Train), in a 98.8 minute orbit with a 1:30 PM nodal crossing time and a 16-day (233-orbit) ground-track repeat cycle. The OCO-2 spacecraft carries and points a three-channel, imaging, grating spectrometer. This instrument is designed to collect high-resolution, co-bore-sighted spectra of reflected sunlight within the molecular oxygen (O₂) A-band near 765 nm, and within the CO₂ bands near 1610 and 2060 nm with a resolving power⁷ around 20,000. These three absorption bands overlap the NIR and SWIR channels used by the GOSAT TANSO-FTS to record O₂ and CO₂ spectra.

Each OCO-2 spectral channel records three samples per second continuously in eight spatial footprints along a narrow (approx. 10 km) ground track. This sampling approach yields about one million soundings over the sunlit hemisphere each day or almost 100 times as many soundings as GOSAT.

⁷ The resolving power of a spectrometer is defined as $\lambda/\Delta\lambda$, where $\Delta\lambda$ is the smallest difference in wavelengths that can be distinguished at wavelength λ .

Preliminary results indicate that about 13% of these soundings are sufficiently cloud free to yield full-column XCO_2 estimates with single sounding random errors are near 0.5 ppm at solar zenith angles as high as 70 degrees.

For routine science observations, the OCO-2 spacecraft points the instrument's field of view either at the local nadir or toward the "glint spot" where sunlight is specularly reflected by the Earth's surface. The instrument collects soundings along a narrow (< 10.6 km) swath near the observatory's fixed ground track. Individual ground tracks are separated by $\sim 25^\circ$ of longitude on any given day, but this distance is reduced to roughly half within two days and to only 1.5° of longitude after 16 days. Nadir observations maximize the spatial resolution and minimize the surface footprint area, reducing biases associated with sub-footprint clouds or topographic variations over continents. Glint observations provide much higher signal levels over dark ocean surfaces. In addition to these two routine pointing modes, OCO-2 can point the instrument at stationary surface targets and scan across the target acquiring thousands of soundings as it flies overhead. This mode is primarily used to collect data over surface validation sites, included Total Carbon Column Observing Network (TCCON) stations.

The initial observation strategy acquired only glint or nadir observations over the entire sunlit hemisphere for a complete, 16-day, ground track repeat cycle, and then used the other observation mode in the next 16-day cycle. This approach optimized the coverage of oceans and continents on monthly time scales, but produced 16-day long gaps in the coverage of the ocean while in nadir mode, and limited coverage of high latitude continents while in glint mode. In early July of 2015, this observation strategy was modified to alternate between glint and nadir observations on alternate orbits to obtain more continuous coverage of the entire sunlit hemisphere every day. A preliminary map of OCO-2 XCO_2 observations is shown in Figure 7.

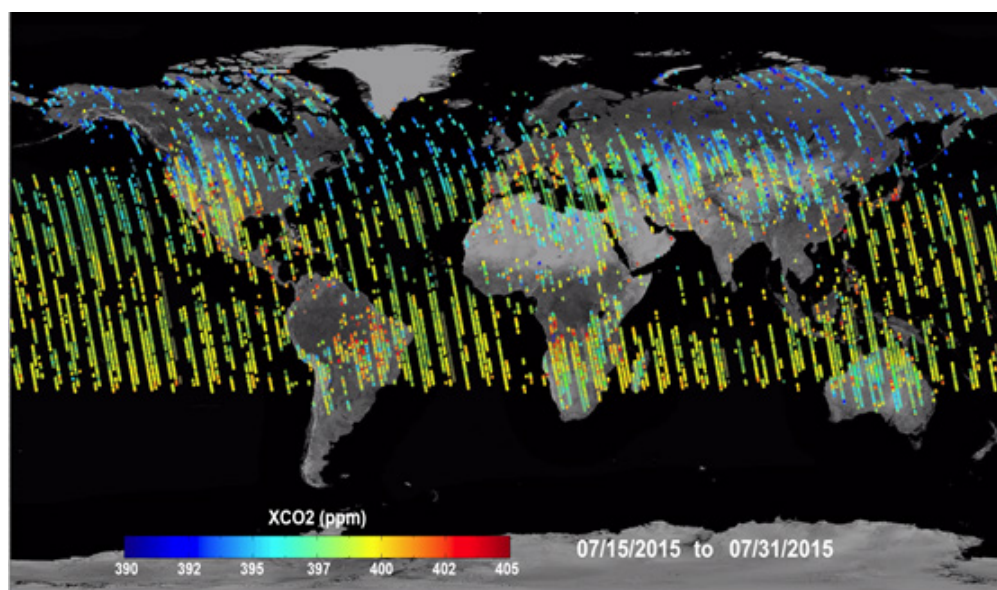


Figure 7. Cylindrical projection of the Earth with OCO - 2 XCO_2 observations, bias corrected from the OCO-2 B7 "Lite" product, taken in the period 15-31 July 2015. Courtesy NASA/JPL-Caltech.

Planned Greenhouse Gas Missions

TanSat (expected in 2016): The Chinese Carbon Dioxide Observing Satellite, TanSat, is currently under development by the Ministry of Science and Technology of China (MOST), Chinese Academy of Sciences (CAS), and National Satellite Meteorological Center (CMA). TanSat is currently scheduled to launch in July of 2016. At the time of writing, the plan was to fly TanSat in the A-Train. The ~ 500 kg spacecraft will carry and point two instruments at nadir, sun glint and stationary surface targets. The primary CO_2 monitoring instrument is the High Resolution Hyper-Spectral Sensor for carbon observation Grating Spectrometer (HRHS-GS). This is a high-resolution, 3-channel grating spectrometer designed to record spectra of reflected

sunlight within the 0.76 μm O₂ A-band, and the CO₂ bands centered near 1.61 and 2.06 μm . The resolving power in the A-band is near 21,000, while that in the CO₂ bands is near 12,000. The footprint size is ~2 km by 2 km and the swath is 20 km wide at nadir. This instrument will be complemented with the Cloud and Aerosol Polarization Imager (CAPI). This instrument will record images in 5 spectral channels (0.38, 0.67, 0.87, 1.375, and 1.64 μm) with a spatial resolution of 0.5 km over a 400 km wide swath. The 0.67 and 1.64 μm channels sample 3 independent polarization angles. Soundings recorded by the spectrometer will be used to retrieve XCO₂, while data from CAPI will be used to correct cloud and aerosol interference. The target accuracy of the CO₂ measurements is 1 to 4 ppm on regional scales (500 km x 500 km) and monthly time scales. The current plan is to validate these results against a comprehensive, multi-site ground based measurement network in China as well as other internationally-recognized standards.

GOSAT-2 (expected in 2018): JAXA, NIES, and the Ministry of the Environment, Japan, have started to formulate a follow-on mission for GOSAT, called GOSAT-2. While GOSAT data are currently analyzed to yield single-sounding XCO₂ and XCH₄ estimates with precisions of ~0.5%, the goal for GOSAT-2 is to return results as much as four times more precise on regional scales at monthly intervals. This will require improved measurement sensitivity and accuracy together with more versatile pointing capability and retrieval algorithms which are more robust to cloud and aerosol contaminations and noise. To meet these objectives, GOSAT-2 will carry more advanced versions of the instrument TANSO-FTS and TANSO-CAI instruments carried by GOSAT. The current plan is to fly GOSAT-2 in a 613 km, sun synchronous orbit with a 6-day ground track repeat cycle and a 1300 +/- 15 minute nodal crossing time.

TANSO-FTS-2, includes updated optics and detectors to produce larger signal to noise ratios for similar integration times and surface footprints. These updates, combined with intelligent pointing, are expected to yield at least twice as many usable, cloud-free soundings. The spectral ranges and spectral resolution within each spectral channel have been optimized to yield improved sensitivity to O₂, CO₂ and CH₄ variations. An additional channel has been added near 2.3 μm to measure carbon monoxide (CO). Modifications to the scan mechanism have been adopted to facilitate observations of the bright ocean glint spot over twice the range of latitudes to improve the instrument's sensitivity to CO₂ changes over the ocean. Improvements in the performance of the TANSO-CAI are also needed to meet the much more stringent GOSAT-2 goals. The current plan is to launch GOSAT-2 in early 2018 and to operate it for at least 5 years.

OCO-3 (planned): As part of the OCO-2 mission, NASA authorized the development of a flight spare instrument to minimize schedule impacts of any delays introduced by problems with the flight instrument development. In November 2012, NASA approved a Phase-A effort to adapt this instrument for deployment on the International Space Station (ISS) as the Orbiting Carbon Observatory-3 (OCO-3). The plan is to install OCO-3 on the Japanese Equipment Module Exposed Facility (JEM-EF) as early as 2018 for a 3-year nominal mission.

Because OCO-3 is based on the OCO-2 spares, its physical characteristics, capabilities, and performance are expected to be similar to that of the OCO-2 instrument. Like that instrument, OCO-3 can collect a larger number of useful soundings over land by pointing the instrument's field of view (FOV) near the local nadir, while over the ocean, the instrument's FOV must be pointed near the apparent glint spot to collect adequate signal for XCO₂ retrievals. To validate estimates of XCO₂ derived from OCO-3 measurements, its FOV must also be able to track stationary surface targets, such as TCCON stations, as the ISS flies overhead and collect large numbers of soundings. For OCO-2, the instrument's field of view is pointed by an agile spacecraft bus. To enable these pointing capabilities from a nadir-pointing platform like the ISS, the OCO-2 flight spare instrument was augmented with an agile, 2-axis pointing mechanism. While this pointing mechanism and other modifications needed to accommodate the sensor on the ISS will add complexity to the instrument, these changes provide new opportunities for mapping compact targets, such as cities, power plants, or coastlines.

Unlike SCIAMACHY, GOSAT, and OCO-2, which fly in near-polar, sun-synchronous orbits, ISS flies in a low inclination orbit, which overflies latitudes equatorward of 51° . This orbit will preclude coverage of higher latitudes, but will provide somewhat better coverage of mid-latitudes, where human activities emit the most CO_2 . Mid-latitude measurements from OCO-3 would be most easily interpreted if they were acquired along with others from a polar orbiting system, like OCO-2 or GOSAT. The orbit precession will allow OCO-3 to sample different parts of the Earth at different times of day. This will provide the first opportunity to search for variations XCO_2 and other carbon cycle variables, such as chlorophyll fluorescence, across the entire range of local times from dawn to dusk from a single space-based platform.

MicroCarb (expected 2020): MicroCarb, intended to be launched by the French Space agency, Centre National d'Études Spatiales (CNES), will be the first European satellite designed to measure atmospheric CO_2 from space with the precision and resolution needed to characterize (mostly natural) CO_2 sources and sinks at regional scales. MicroCarb is currently being targeted to launch in 2020, and fly in the A-Train, providing opportunities to extend the CO_2 data record initiated by OCO-2. MicroCarb consists of a micro satellite that carries a compact, high resolution, 3-channel, grating spectrometer designed to measure the absorption of reflected sunlight in the same spectral bands used by OCO-2. To achieve a very compact design (thereby optimizing mass size and cost) the spatial resolution of MICROCARB will be approximately 5 km with no across swath spatial imaging. The targeted random error is of 1 ppm for individual soundings.

CarbonSat (not recommended for Earth Explorer 8): CarbonSat is the first mission designed to disentangle anthropogenic from natural emissions of CO_2 and CH_4 (Bovensmann et al 2010, Buchwitz et al 2013, ESA 2015) using the greenhouse gas imaging approach to provide images of atmospheric CO_2 and CH_4 from emission hot spots. CarbonSat is designed to fly in a near-polar, sun-synchronous orbit with an 11:30 AM nodal crossing time. CarbonSat carries a single, high spatial resolution imaging grating spectrometer that measures reflected sunlight in three broad spectral intervals covering the O_2 A-Band (747-773 nm, FWHM=0.1 nm), the CO_2 and CH_4 bands at 1590-1675 nm (FWHM=0.3 nm), and the CO_2 and H_2O bands at 1925-2095 nm (FWHM=0.55 nm), with three to six samples per FWHM in each channel. The CarbonSat spectrometer has somewhat lower spectral resolution than the GOSAT or OCO-2 and it records reflected sunlight in optimized regions to better characterize chlorophyll fluorescence near 750 nm and cirrus cloud near 1950 nm. Its $\sim 4 \text{ km}^2$ surface footprints (at nadir) yield a spatial resolution that is comparable to that of OCO-2, but for a much broader cross-track swath ($> 240 \text{ km}$), to provide complete coverage of the sunlit hemisphere on weekly to monthly intervals. With this broad swath, CarbonSat collects up to ten times as many cloud-free soundings each day as OCO-2. The individual random error on each sounding is 1-3 ppm, and systematic error 0.2-0.5 ppm. The high spatial resolution and more complete global coverage should allow the creation of high resolution, two-dimensional images of strong surface sources of CO_2 (and CH_4). CarbonSat was a candidate⁸ for the 8th ESA Earth Explorer mission but was not recommended by the ESAC science advisory committee in Sep. 2015.

MERLIN (expected in 2019 – measuring CH_4): The Methane Remote Sensing Lidar Mission (MERLIN) is a joint German-French mission to measure CH_4 , using an active laser (lidar). It will be the first mission able to detect CH_4 sources and sinks in the high latitudes between the Autumn and Spring Equinox, and is expected to deliver an unprecedented knowledge of the global and regional distribution of CH_4 fluxes. of the global and regional distribution of CH_4 fluxes, including some emissions hot-spots. MERLIN is the first space mission to use a lidar for measuring CH_4 . This active sensing approach has a very narrow ground footprint and can collect measurements during both day and night, in all seasons, and at all latitudes. Unlike the passive instrument, the lidar will not make an oxygen measurement to infer the dry air mass. Instead, it will use assimilated meteorological data products for surface pressure, temperature, and water vapor information. MERLIN is currently scheduled for launch in 2019.

⁸ The other candidate was the Florescence Explorer (FLEX).

ASCENDS (planned): The NASA Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) mission will use active laser (lidar) methods to extend the coverage of XCO₂ measurements to the night side hemisphere of the Earth and to high latitudes during the winter. A larger fraction of the ASCENDS measurements are expected to be cloud free in partly cloudy conditions, because of the near-vertical nature of both its illumination and measurement paths. While the specific instrument and mission architecture have not yet been selected, current studies are targeting a measurement precision of ~1 ppm over 10-second integrations along the orbit path in cloud-free conditions. The spacecraft will most likely be deployed in a low altitude (400-500 km) sun-synchronous orbit with a midday/midnight sampling time. Measurements will be collected along a narrow (~0.1 km) ground track near the spacecraft nadir. Individual samples will have small ground footprints, but samples collected over periods as long as 10 seconds may have to be co-added to meet the XCO₂ precision requirements.

A series of studies are currently underway to refine the science objectives and implementation approach for this mission. Observational System Simulation Experiments (OSSE's) are being performed to define the science, measurement, and mission operations requirements. Aircraft campaigns are being conducted to assess the relative performance of instrument architectures including continuous and pulsed lidar technologies for measuring CO₂ at 1.57 and 2.05 μm and O₂ at 0.764 and 1.26 μm . Mission studies are being performed to assess the spacecraft, launch vehicle, and mission operations requirements. While the final mission design has not yet been selected, these design activities have identified no technical show stoppers. Unfortunately, the launch date continues to be delayed (now sometime after 2022).

Copernicus Sentinel-5p (2016), Sentinel-4 (2020), and Sentinel-5 (2021): Within the European Copernicus programme, three main atmospheric missions are being prepared for launch in the coming years. Their focus is on observing atmospheric composition, but fossil CO₂ emissions is currently not within their remit. The Sentinel-5 Precursor mission is a polar orbiter intended to provide data continuity for the SCIAMACHY instrument aboard the EnviSat satellite and NASA's OMI instrument aboard the Aura satellite in the interim between the end of the EnviSat and Aura missions and the launch of Sentinel-5. It will provide measurement of O₃, NO₂, SO₂, HCHO, CO, CH₄ and aerosol using three spectral bands: 270-495 nm, 710-775 nm, and 2305-2385 nm. Its launch date is foreseen for mid-2016.

The Sentinel-4 mission focuses on monitoring of trace gas concentrations and aerosols in the atmosphere with a high revisit time over Europe. The Sentinel-4/UVN instrument is a high-resolution spectrometer system operating with 3 designated bands in the solar reflectance spectrum, covering the ultraviolet (305-400 nm), visible (400-500 nm) and near-infrared (750-775 nm) bands. It will have a spatial sampling of 8 km over Europe and a fast repeat cycle over Europe and North Africa (Sahara) of 60 minutes. The main species to be measured are O₃, NO₂, SO₂, HCHO and aerosol optical depth. Neither CO₂ nor CH₄ will be delivered by Sentinel-4. The instrument is scheduled for launch after 2019 on board the MeteoSat Third Generation (MTG) series of satellites.

The Sentinel-5 mission will focus on monitoring of trace gas concentrations and aerosols in the atmosphere to support operational services covering air-quality near-real-time applications, air-quality protocol monitoring and climate protocol monitoring. The Sentinel-5/UVNS instrument is a high-resolution spectrometer system operating in the ultraviolet to shortwave infrared range with 7 different spectral bands: UV-1 (270-300nm), UV-2 (300-370nm), VIS (370-500nm), NIR-1 (685-710nm), NIR-2 (755-773nm), SWIR-1 (1590-1675nm) and SWIR-3 (2305-2385nm). Its spatial resolution is below 8km for wavelengths above 300nm and below 50km for wavelength below 300nm. The main data products will be O₃, NO₂, SO₂, HCHO, CO, CH₄ and aerosol optical depth, which thus does not include CO₂. The instrument will be hosted by the Metop-SG platform, which is currently expected to launch after 2020.

Other Vantage Points: Geostationary (GEO) and Highly Elliptical Orbits (HEO)

Observations of CO₂ and CH₄ from satellites in low Earth orbit (LEO) like those described above can provide observation of the entire globe from a single platform. However, the temporal sampling from LEO is limited to a single overpass ever very few days (or weeks), and LEO observations from sun synchronous orbits sample the Earth at a fixed time of day. Observations from sensors in Geostationary Orbit (GEO) would be highly complementary to these LEO observations. GEO satellites, stationed above a fixed point over the equator, can provide high frequency measurements at latitudes as high as ~50 degrees throughout the sunlit part of the diurnal cycle. A set of as few as 3 GEO missions could provide high frequency observations of critical longitudes including (i) 60-75 W: the Amazon and Eastern USA, (ii) 0-5 E: Central Africa and Europe, and (iii) 130-140 E: Australia, Indonesia, and East Asia. Additional GEO platforms stationed over the Indian Ocean and Western USA would provide more complete coverage of the globe, similar to that of the current meteorological space observations. Continuous observations over the high latitudes are not possible from GEO. These observations could be carried out by deploying sensors on satellites in highly elliptical orbit (HEO) with their apogee over the North Pole.

Currently, there are no explicit plans for greenhouse gas measurements from GEO or HEO platforms (Figure 8), but several mission have been proposed in the USA and Europe and these missions have received an endorsement from the Committee on Earth Observation Satellites (CEOS) Carbon Task Force Report (CEOS 2014). An interesting greenhouse gas set of instruments would include sensors on a minimum of 2 to 3 LEO satellites, 3 GEO platforms, and at least one HEO satellite. This combination of LEO and GEO platforms is used as well in the current meteorological network. Some cost savings could be realized in the long term if CH₄ and CO₂ instruments could be manifested on those platforms. In addition, like the existing, multinational meteorological satellite system, each nation or international confederation could contribute to only part of the network. This approach would work only if the instruments can be cross-calibrated, their measurements can be cross-validated, and these data are exchanged freely among all partners. The strong, ongoing collaboration between the Japanese GOSAT and NASA OCO-2 teams provides a useful pathfinder for these capabilities.

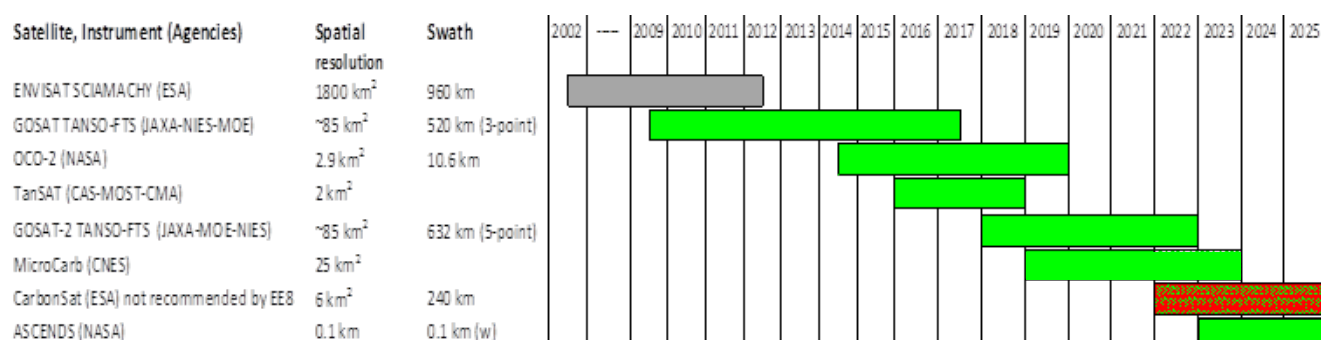


Figure 8. Recent, current and planned missions for atmospheric CO₂ column measurements. Green = missions that will advance knowledge of natural fluxes. Red hatching = mission that provide information for separating emissions from natural fluxes. Note that OCO-2 and GOSAT, GOSAT-2 have pointing capabilities that allow focus on some emitting hotspots if desired, but the prime objective of these missions is to quantify the large scale distribution of natural fluxes. CarbonSat was not recommended by the science advisory committee of ESA, for the Earth Explorer 8 program.

4. Operational processing of emissions: data requirements combining inventory, in-situ and Earth-Observation data

We recommend the development of an observation system for CO₂ emissions to be used within a Fossil Fuel Data Assimilation System (FFDAS) in order to combine:

- 1- Emission inventory information.
- 2- Column integrated satellite CO₂ measurements, possibly completed by satellite measurements of combustion tracers related to fossil CO₂ emissions (e.g., CO).
- 3- In-situ atmospheric measurements of CO₂ and tracers (e.g., CO, ¹⁴C).

We recommend the development of emission inventories to become available on an operational basis at detailed spatial (1 x 1 km) and temporal (hourly) resolution, with a near-real-time production capability, in order to supply prior information to an atmospheric inversion system. This capability exists on a research basis in major European inventory groups but will need to be developed for operational requirements.

We recommend to build urban monitoring networks for selected European large cities. Results from city-scale inversions of CO₂ data from urban networks will be used to evaluate independently satellite-based city-scale emission estimates. ¹⁴C measurements should be deployed a set of approximately 50 atmospheric CO₂ monitoring stations across the European continent, with higher density over regions with high emissions. Results from regional- and continental-scale inversions of in-situ ¹⁴C and CO₂ measurements will be used to evaluate independently satellite-based emission estimates.

We recommend to maintain the TCCON network of ground based total-column CO₂ measurement stations, and expand its coverage in cities and areas with high fossil CO₂ emissions. Data from the TCCON network will provide a critical validation resource for space based remote sensing observatories.

A first satellite mission measuring XCO₂ with capabilities for resolving fossil emissions should be launched by 2025. Follow-up European contribution could then consist of four satellites by 2030. Four instruments with characteristics comparable to e.g., the CarbonSat instrument could provide a daily coverage of the well-sunlit part of the Earth each ≈ 7 days at the equator and each ≈ 3 days in the mid-latitudes, and so deliver data suitable to improve emissions estimates and monitor their trends.

We recommend that detailed end-to-end simulations of the performances of an operational observation system of fossil CO₂ emissions should be carried out for different satellite and in-situ networks configurations.

Such a CO₂ capacity system should exist within and rely upon the wider set of Copernicus services to develop an operational atmospheric inversion system for monitoring fossil CO₂ emissions and emission changes.

Background

As described in **Chapter-2**, the inversion of surface CO₂ fluxes in general, and of fossil emissions of CO₂ in particular, using satellite and ground-based observations is a challenging task. Much progress has been made on larger spatial and temporal scales, and recent advances further improved the flux estimates at smaller scales. Bringing such a rapidly developing framework for fossil emissions quantification to an operational environment brings of course more challenges.

The underlying principle of operational processing is that observations, from satellite and ground-based systems, are routinely processed with clearly defined performance indicators (accuracy, timeliness, etc.) that are continuously being monitored. Observations are routinely processed as soon as they become available and ideally as close to real-time as possible with a time frequency that depends on the exact application and which can range from sub-daily to annually.

The relevant user groups should be clearly identified and the products of the operational system should be served to these users through well-defined interfaces with sufficient support and documentation. In addition, these users should be included in requirement reviews and as such provide input to the development of the operational system. It is important to note here that the definition of users for such an operational system needs to be carefully addressed. The operational processing of observations could for instance be staged with intermediate users translating the outcomes of the basic system to end-users. For instance, policy makers require very different products than the science community and this cannot necessarily be addressed by one single operational system. Finally, key to a robust operational system is the sustainability, in terms of funding, availability of the needed observations, and the further development of the processing systems. For the latter, it is clear that operational systems are developed from similar research systems and need to stay closely linked to developments of these research systems.

In terms of operational requirements for the input satellite data, two key aspects are mentioned here. Firstly, because of its required robustness, an operational system is designed with some degree of inertia. Any changes to the system should ideally be tested on their impact before being implemented. This also applies to input data and it is therefore important that changes in for instance satellite retrieval products are communicated well in advance.

Secondly, using more than one data source in an assimilation/inversion system means that great care should be given to systematic differences between the data products. Bias correction is central to any operational data assimilation system, but is even more important in the case of CO₂, for which very small systematic errors can lead to very significant errors in the flux results. Validation and inter-comparison between the satellite products constitute therefore a crucial part of an operational processing chain.

Various research projects have developed flux inversions systems that can or could use satellite observations to estimate surface fluxes of CO₂ (CarbonTracker, TRANSCOM, MACC, CARBONES, CCDAS) (see also GEO Carbon Strategy 2010 by Ciais et al. (2010b)). The focus of these inversion methodologies has been on natural biosphere and ocean fluxes and not so much on anthropogenic emissions. Based on the significant progress of these research activities, frameworks are now being set up to bring them to a more operational level with longer term perspective. Within the United States this has for instance resulted in the definition of the NASA Carbon Monitoring System (CMS), which is a forward-looking initiative designed to make significant contributions in characterizing, quantifying, understanding, and predicting the evolution of global carbon sources and sinks through improved monitoring of carbon stocks and fluxes. The aim is to use the full range of NASA satellite observations and modeling/analysis capabilities to establish the accuracy, quantitative uncertainties, and utility of products for supporting national and international policy, regulatory, and management activities (<http://carbon.nasa.gov/>).

Within Europe, the Copernicus programme is funding operationalization of the research activities as part of the Copernicus Atmosphere Monitoring Service (CAMS). Two applications are currently defined within CAMS (<http://atmosphere.copernicus.eu>) to infer information about CO₂ from satellite and ground-based observations. The first application is the use of satellite data and ground-based data in a comprehensive atmospheric data assimilation and forecasting system generating best estimates of the state of atmospheric CO₂ (and other relevant variables) and its progression over the next several days. This method combines information from models, a priori data, and the actual observations at high spatial (15 km) and temporal resolution (hourly) and is meant to monitor atmospheric CO₂ concentrations, detect and correct inconsistencies between observations from various satellite sensors, and support interpretation of the various observational data sets by providing a global view at high spatial and temporal resolution. Because of its very high resolution this system is very well placed to further investigate the impact of anthropogenic emissions on the distribution of atmospheric CO₂ and therefore support the future development of inversion methods which aim to infer emission estimates from satellite observations.

The second current operational application is the provision of inverse flux estimates of natural fluxes using both satellite and ground-based data. These inverse systems are very similar to research systems, but, being operational, are run in a routine manner. Observations are generally processed at intervals of 6 months to a year at a typical spatial resolution of a few hundred kilometers, but this could be adapted to higher resolution given sufficient resources. While the use of satellite observations has been rather successful for CH₄ flux inversions (SCIAMACHY and GOSAT), it has been more difficult to obtain accurate results in the case of CO₂. The observation requirements for accurate flux inversion results are very stringent with a requirement for systematic errors of better than 0.5 ppm (Buchwitz et al., 2015a). Also, as mentioned earlier, anthropogenic emissions are still being prescribed in these inversions using information from inventories.

The reasoning behind having two application areas is to provide operational products from state-of-the-art assimilation and inversion systems that can on the longer term be merged in a more comprehensive system that uses satellite and in-situ observations with high-resolution modelling to provide accurate CO₂ flux estimates. However, this will require further development of all components of such an inversion system as well as significantly increased computing resources.

Finally, WMO has set up the Integrated Global Greenhouse Gas Information System (IG3IS) activity. IG3IS (<https://www.wmo.int/pages/prog/arep/gaw/ghg/IG3IS-info.html>) would combine ground-based and space-based observations, carbon-cycle modeling, fossil fuel-use and land-use data, meta-analysis, and an extensive distribution system to provide information about sources and sinks of greenhouse gases at policy-relevant temporal and spatial scales. These scales, of necessity, must reside at sub-continental levels. Modeling and observing capabilities will determine the granularity and value of the information. IG3IS is envisioned as an international, independent, observationally based information system for determining trends and distributions of GHGs in the atmosphere and the ways in which they are consistent or not with efforts to reduce greenhouse gas emissions at a much finer spatial and temporal scale than is currently possible.

In the following, we describe the evolution / transformation that will be needed for the provision of inventory information, in-situ data, and Earth Observation data to a future operational inversion model for monitoring fossil CO₂ emissions.

Emission inventories data

Emission inventories will have to be available on an operational basis at detailed spatial (1 x 1 km) and temporal (hourly) resolution, with a near-real-time production capability, in order to supply prior information to an atmospheric inversion system or FFDAS.

Until now there are only limited experiences with high spatial and temporal data for CO₂ emissions, but for the short-lived air pollutants this has received more attention. Air quality studies have shown that much higher spatial and temporal resolution is possible, especially when combining traditional emission inventory approaches with emission modelling and (near) real time data. Good examples exist for road transport (Scora et al., 2011; Samaranayake et al., 2014; Mues et al., 2014) and shipping (the use of automatic identification systems (AIS) data to get accurate (with a resolution of seconds) spatial information on ship type and speed that can be used to accurately model shipping emissions (Jalkanen et al., 2015)). This kind of emission modelling can bring the prior emissions data input for the modelling system to a next level, thereby greatly reducing the uncertainty in the inversion system leading to much higher accuracy in final predicted (country/ county) emission estimates. This information is not yet available for CO₂ on a large scale nor over longer time series but the capabilities exist. This approach would also tackle the delay in availability of emission inventories. The cumulative emissions predicted on an hourly or daily basis would result in a first estimate of the annual emissions immediately at the end of each year. When the traditional inventories become available with a lag of two years (or more) a reanalysis could be made to further improve a CO₂ emission model and/or highlight weaknesses in the current inventories. Near-real time emission estimates could be provided not only for CO₂ but also for the co-emitted species bringing further detail in the source sector allocation of the modelling. Increase of resources (e.g., staff, computing time and big data handling) will be needed to go from capability (now) to a research prototype (by 2020) to an operational product by the 2030s.

Earth Observation data

A first European satellite mission measuring XCO₂ with capabilities for resolving fossil CO₂ will be needed by 2025. The possibility to measure carbon monoxide (XCO) in addition to XCO₂ should be considered to help separate emissions from surrounding biogenic fluxes.

Follow-up European contribution could consist of three satellites launched by the 2030s. With four space-borne instruments having characteristics comparable, e.g., to the CarbonSat instrument, a daily coverage of the well-sunlit part of the Earth could be achieved each four days, bringing data suitable to improve emissions estimates and monitor their trends.

Since the coverage of the high latitudes in winter will remain low with passive instruments only, synergies between passive and active sensors by 2030s should be explored, both to improve the accuracy of XCO₂ from passive sensors and their coverage of the high latitudes in winter. Satellites with pointing capabilities could also improve the coverage of emissions hotspots by more frequent sampling of cities and large point sources.

Optimal design of the space component of a fossil CO₂ emissions observation system will require end-to-end performance simulations that are outside the scope of this report. Thus, detailed end-to-end simulations of the performances of a fossil CO₂ emissions observation system should be carried out for different satellite configurations and different in-situ networks scenarios, by using Observation System Synthetic Experiments, with state of the art inversion models.

Since the EO data for monitoring will likely come from different space-borne instruments, possibly associated with different data retrieval algorithms, the measurements should be cross-calibrated and the retrieved XCO₂ (or XCH₄) estimates cross-validated against internationally recognized standards to meet the objective of developing an operational observation system for fossil CO₂ emissions.

As shown in Figure 9, the current set of missions mainly addressed the need to observe natural CO₂ fluxes, to the exception of OCO-3 and CarbonSat (not recommended by the science advisory panel of ESA in the Earth Explorer 8 programme). CarbonSat is designed as an exploratory mission designed to provide images of emissions hotspots, from which emissions at the time (few hours before) of satellite overpass can be constrained. Routine estimation of emissions will need more frequent revisits, if possible at different time of the day, given diurnal changes of fossil CO₂ emissions (Chapter-1). Because cloud coverage excludes XCO₂ measurements from space, dense spatial sampling (to obtain enough data) and dense temporal sampling (to track emissions at different times of days, weeks, years) are critical. A notional timeline for developing a European contribution to a global combination of satellites with capabilities to resolve emissions is given in Figure 9. Future missions “CO₂ in Copernicus” are the space component of the observing system described in this report.

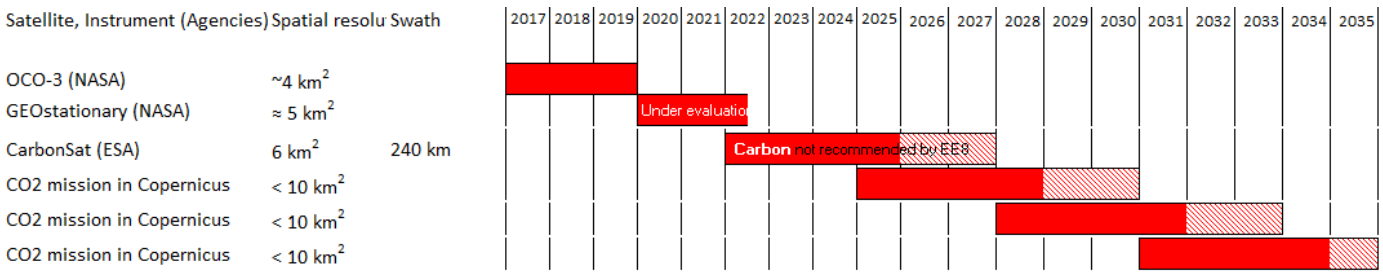


Figure 9. Future satellite missions with capabilities to resolve fossil fuel CO₂ emissions. OCO-3 will focus on cities emissions. CarbonSat was not recommended by the science advisory committee of ESA, for the Earth Explorer 8 program. The other three missions named “CO₂ mission in Copernicus” could be part of a dedicated European Copernicus-CO₂ program.

In-situ data

Data from existing in-situ networks described in the following paragraphs are currently insufficient to bring independent information to improve fossil fuel CO₂ emission. In order to enhance in-situ data and to resolve fossil CO₂ emissions, some major evolutions are recommended.

Urban networks Experience from a pilot network of four stations deployed around the Paris area showed that total CO₂ emissions inventories for this city could be constrained and their uncertainty reduced (Bréon et al., 2014). Further design studies with a hypothetical larger network of stations (Wu et al., 2015) showed that a dense urban network of sensors of moderate precision (1 ppm) could even separate emissions from different main sectors, in addition to reducing the uncertainty of total city CO₂ emissions down to 5%, which is comparable to the accuracy achieved now at national scale by the best inventories (Chapter-1). Some additional urban CO₂ stations have been installed near London, Berlin and Rotterdam.

Although urban networks cannot be deployed for every city in Europe, unless a breakthrough in cheap, low maintenance and yet accurate sensors cost could be achieved, we recommend that more urban networks to be built in the next decade (by 2025) over major European cities. These data, coupled with regional inversions will bring an independent validation of CO₂ emissions retrieved from satellite observations such as described in Chapter-3. It is important to ensure that these urban CO₂ measurements will be calibrated on the same international WMO scale as continental scale networks, to warrant consistency between local city scale inversion results and satellite-based inversion results.

¹⁴C network: The abovementioned urban networks could only realistically cover some of the largest cities and will likely never achieve a complete coverage of all the emissions within a country. The first simulations of a ¹⁴C observation system (Wang et al., 2015) based on a network of in-situ stations across Europe indicated that with weekly sampling, national fossil CO₂ emission budgets over a year could be independently verified with a typical accuracy of 10% for middle-sized countries. With daily sampling, a larger uncertainty reduction could be obtained. ¹⁴C can be treated in inversions as representing a fossil fuel CO₂ tracer, but for a more accurate separation of fossil fuel CO₂ emissions from natural fluxes, it will be useful to include ¹⁴C emissions from nuclear reactors and nuclear fuel reprocessing industry, as well as the fluxes exchanged by soils.

This could be initiated at existing stations by ≈2025, completed by denser coverage of stations in areas where the strongest emission uncertainty reduction will be gained (by ≈2030). Note that in-situ urban networks and regional ¹⁴C networks in-situ observing systems are complementary to each other, one (urban networks) allowing to measure some hotspots of emissions and the other (¹⁴C continental-scale networks) giving a top-down verification of emissions budgets aggregated over larger spatial scales, such as regional or national scale.

TCCON network of ground based total-column CO₂ measurements: A third evolution is to maintain the TCCON network of ground based total-column CO₂ measurement stations (<http://www.tccon.caltech.edu>) and to expand its coverage in cities and areas with high fossil CO₂ emissions. Data from the TCCON network will be an important component of an emission monitoring system, to ensure the validation of XCO₂ (and XCO) from space, allowing to detect independently possible instrument drifts or changes in data retrieval procedures that might cause XCO₂ to differ between space-borne sensors or to be affected by temporal or regional biases. Biases of XCO₂ are of particular concern for a system designed to improve emission inventories because even small biases of atmospheric measurements will translate into biases in the CO₂ flux maps. The TCCON data can be made traceable to the same international WMO CO₂ mole fraction scale using aircraft validation campaigns, ensuring that satellite observation, which will come in much denser quantities than in-situ ground based data will not bias the results of flux inversions in case of systematic errors. Other stratospheric measurements such as air core measurements can also be used for the calibration.

AIRCRAFT measurements: Another in situ measurements which is currently in the build-up phase and consists of CO₂ sensors built into commercial aircraft providing high-frequency coverage of the troposphere and lower stratosphere (In-service Aircraft for a Global Observing System, IAGOS). In particular the high number of vertical atmospheric profiles obtained during takeoff and landing of the aircrafts is expected to provide important information for inversion models and how they represent vertical mixing.

In an evolution context, like the addition of new satellites or the loss or decline of performance in an instrument, it is important that both the TCCON stations and the CO₂ in-situ ground based stations can be maintained for long term operations, and deliver continuous measurements at a stable level of (high) accuracy.

The Copernicus program

Any Copernicus CO₂ programme should rely upon the set of Copernicus services to develop an operational data assimilation system for monitoring fossil CO₂ emissions. Reliable inferences of fluxes from atmospheric observations will require high-quality atmospheric information, both in terms of atmospheric thermo-dynamics and atmospheric composition. This is exactly what has already been established by the Atmosphere Monitoring Service and will be further improved through the service evolution. Furthermore, the attribution of CO₂ fluxes to anthropogenic sources is greatly helped with accurate estimation of other flux components, such as oceanic and biogenic fluxes. These components are to some extent addressed by the Marine Monitoring Service.

Building an operational CO₂ emissions monitoring service on top of these state-of-the-art operational assimilation and modelling systems, in close collaboration with wider research developments, would ensure maximum benefit of existing infrastructure and expertise. The synergy between existing services should culminate on the CO₂ emissions topic in particular in the context of the Copernicus Climate Change Service (C3S).

5. Optimal solutions for an operational independent fossil fuel CO₂ emissions monitoring system

The concrete design of a fossil CO₂ emissions observation system naturally depends on the formulation of the emission relevant agreement or treaty. However, these will likely evolve over time. The propositions here consider a future operational system based on the assumption of independent verification of fossil CO₂ emissions on national, regional to large city scale with a monthly to weekly time resolution capable of verifying large emissions hotspots (i.e. such as big cities and power plants), subnational as well as national budgets, with a precision better than five percent, and systematic errors less than a few percent for the emissions for mid-size countries.

To be able to verify reported inventory emissions, an independent system has to provide estimates of these emissions with an uncertainty comparable to those from the inventory-based estimates. Currently, global annual fossil CO₂ emissions are estimated to have an uncertainty of up to 10% ([Chapter-1](#)), however, on a country scale uncertainties can be larger, especially for developing countries these can be up to several tens of percent (NRC, 2010). These uncertainties, especially for developing countries, are likely to be reduced over time with improved reporting mechanism and further developed accounting methodologies, therefore uncertainty estimates by an independent verification system have to be on the order of a few percent at country-scale.

Based on current knowledge there is an optimal way forward for setting-up an operational independent verification system. In general, such a system consists of a suite of coordinated multi-scale, multi-type carbon observations, a data assimilation system capable of integrating this suite of observations as well as an appropriate data infrastructure and distribution system building upon current research tools and technologies. In addition, a key requirement is that any such operational system that will be put in place needs to be sustained, i.e. to operate over a long-term horizon minimizing any gaps in the observational capabilities. The continuity of the observational data is a critical requirement.

Components of an operational observation system

The notional design of an operational observation system for monitoring fossil CO₂ emissions is given in Figure 10. Such system could be formed by six components:

- **A fossil CO₂ emission inventories operational production component** that receives as input the energy data and emission factors of different economic sectors, and uses activity data to create time varying maps of fossil CO₂ emissions. This component should develop an emission model that can use near-real time (NRT) information to provide NRT emission estimates with a high spatial and temporal resolution. The resulting maps should be “dynamic” in that they should capture weather, behaviour and technological related changes in emissions.
- **An observation infrastructure component including both satellite and in-situ ground based and aircraft data.** This infrastructure is the “engine” of the observation system. Synergies with other observations established, e.g., by US, China is desirable through data sharing agreements, and use of common formats and standards.
- **An atmospheric inversion modelling and data assimilation component** that builds upon research capabilities to develop improved transport models and flux models for non-fossil

fuel CO₂ emissions and sinks, e.g., air-sea fluxes and ecosystem-atmosphere fluxes. Flux and transport models should ideally be fully consistent with each other so that the covariance between transport and weather driving natural fluxes is accounted for.

- **An integration system, building upon the Copernicus services** that carries the inversion of atmospheric observations into optimized emission maps.
- **An Archive / Exchange system** component ensuring that all raw data and data products from the integration are readily available to users.
- **A decision support system** component ensuring that data products from the integration system are properly aggregated into policy relevant information useful for national and EU stakeholders. This system should make use of independent expertise to explain for possible inconsistencies between top-down and bottom up information.

Fossil fuel CO₂ emission monitoring system Scope (notional)

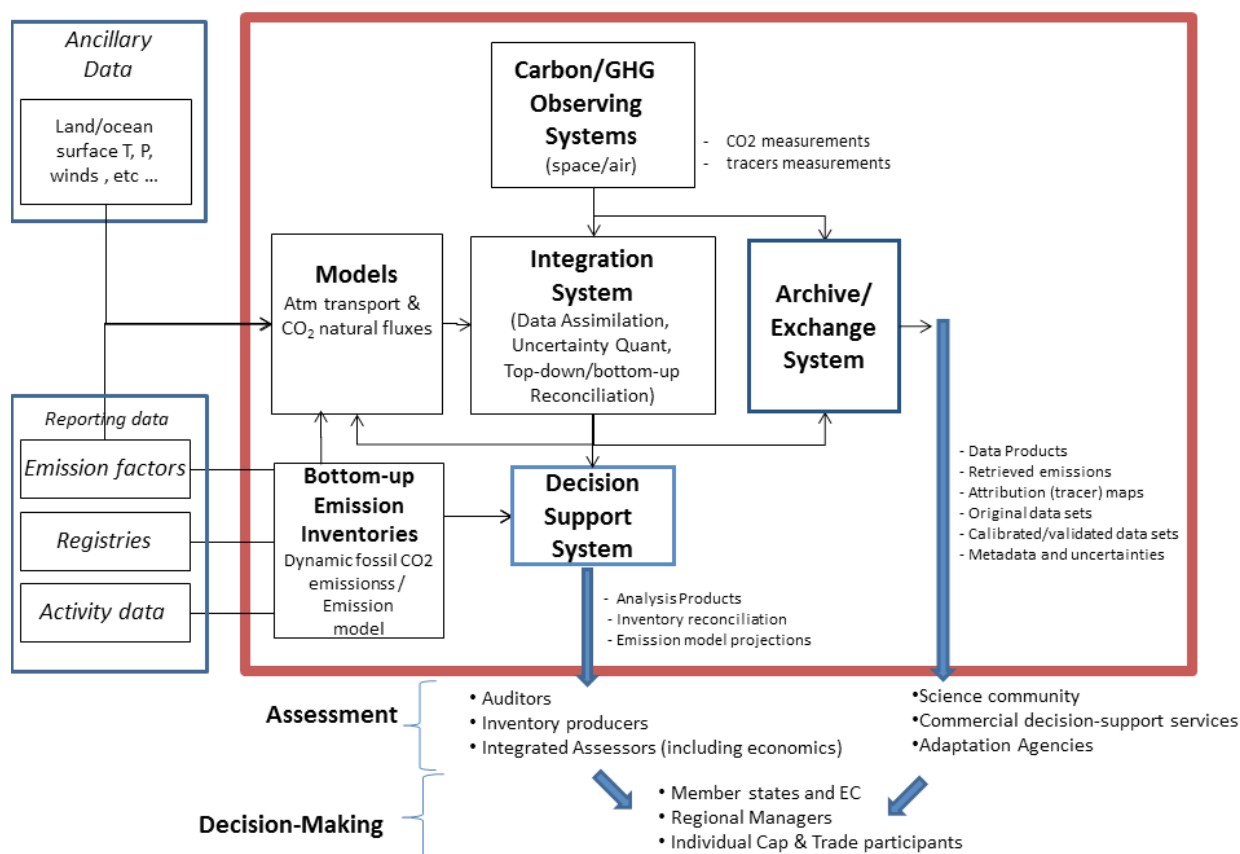


Figure 10. Scope and notional components of a future operational fossil fuel CO₂ observation system (after a figure designed by D. Riley, NASA-JPL).

Development phases

In parallel to the development of a first European CO₂ satellite mission, the optimal design of the operational fossil CO₂ emission observation system should be assessed through a detailed cost/benefit and system engineering analysis, which is beyond the scope of this report. Notionally, the system should be based on three development phases as outlined in Figure 11. Over a period of three years the first phase builds upon existing research tools and monitoring systems, which, in a second phase will be further developed to a pre-operational stage. During this Phase-2 experience will be gained in handling and exploiting remote sensing data from a dedicated CO₂ mission together with improvements in the ground-based monitoring network, modeling

capabilities as well as bottom-up inventories. In Phase-3 this pre-operational system will then be extended to a fully operational verification system. Such a system includes the six components as outlined above.

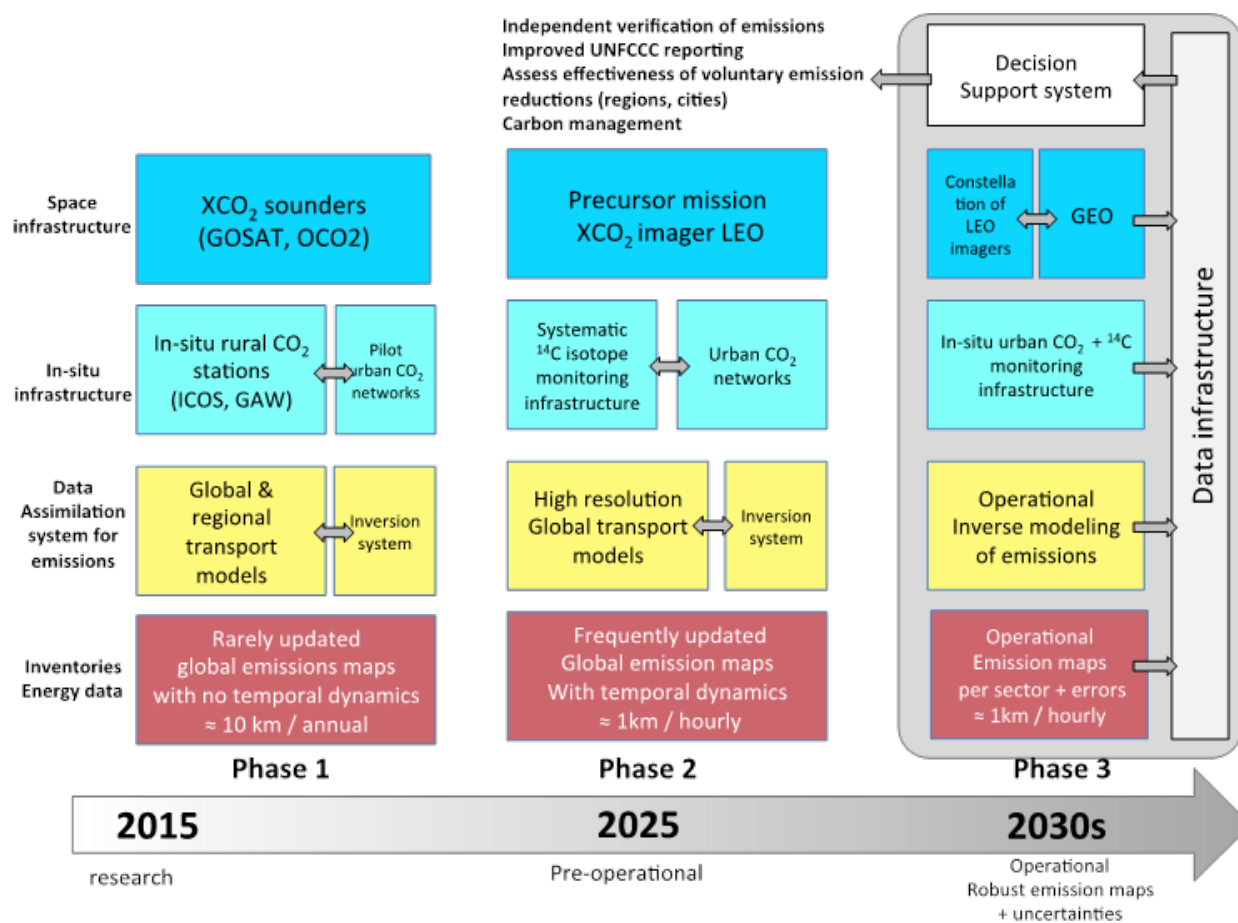


Figure 11. Three different phases in the European contribution to the construction of an operational observation system for monitoring fossil CO₂ emissions.

Remotely sensed observations constitute a crucial component since it provides repeatedly total column CO₂ observations with global coverage from a single instrument overcoming the apparent logistic problems of the ground-based network (national and private sovereignty, accessibility). Hence remote sensing offers spatial coverage superior to any in-situ network. However, to resolve fossil fuel emissions, CO₂ satellite measurements are required to provide XCO₂ precisions of approx. 1 ppm for single observations (Buchwitz et al., 2015a) for individual XCO₂ measurements with systematic errors < 0.5 ppm. The individual ground footprints should be adapted to capture large hotspot emissions and at the same time minimize cloud contamination (size of approx. 2 km), and achieve a complete global coverage (imaging capability) with as frequent as possible repeat passes (ideally at least two times per day) for resolving short-term changes of emissions (e.g., from strong local sources such as large cities or power plants). The column mixing ratio observations should ideally be bias free such that the precision represents the single sounding retrieval errors.

This can most likely be achieved by a combination of LEO imaging instruments, possibly complemented by GEO capabilities, by ≈2030. The instruments will largely be based on today's technology. The dedicated CO₂ missions currently in space have (as outlined in Chapter-4) successfully demonstrated our capabilities to retrieve estimates of total column CO₂ concentration from space. Even though for GOSAT XCO₂ products, the required accuracy is not yet fully achieved, improvements have been made, as shown in the Product Validation and Intercomparison Report of the ESA Climate Change Initiative by Buchwitz et al. (2015b). Retrievals from these missions will be used in phase 1 to develop prototype inversion systems focusing on estimation of fossil CO₂ emissions. These missions, however, are limited in their scope for this purpose because they

are based on sounding instruments. As a development step, a first CO₂ LEO imager has to be launched at the end of Phase 1.

This will enable the community to learn how to use images in inversions and it will further mature the sensor technology. Thus this XCO₂ imager will predominantly be a research-driven, pre-operational mission. At its operational stage the verification system consists, as mentioned above, of a set of imagers within a low Earth orbit, which are possibly complemented by geostationary instruments to achieve the required temporal resolution and spatial coverage.

To achieve and maintain such a high precision and accuracy of satellite XCO₂ observations it is critical to invest in an appropriate validation system (TCCON ground based remote sensing stations). The ground-based Total Carbon Column Observing Network (TCCON) based on 'up-looking' FTIR spectroscopy has been instrumental for validating XCO₂ from current space missions. The TCCON independent, continuous column-average observations, have to be sustained as part of a dedicated CO₂ space program. The current TCCON needs to be extended to cover regions that are critical to emissions monitoring (e.g., megacities) as well as satellite validation (e.g., oceans, deserts).

The space-borne component of an observation system for fossil CO₂ emissions will need to be complemented by ground-based in-situ data. In the first instance, this will be the currently existing network of rural CO₂ measurement stations operated by for instance NOAA, ICOS and others under the GAW program. The NOAA network and many GAW stations have been designed to mainly capture the marine boundary layer baseline CO₂ concentration for identifying large-scale trends in atmospheric CO₂ caused by fossil emissions, whereas the ICOS network aims at quantifying the European carbon budget at regional (sub-national) scales.

Observations from this network together with pilot urban CO₂ networks have been used in research-based projects to estimate the fossil CO₂ emissions at large city scale (Bréon et al., 2015; Boone et al., 2015). During Phase-2, urban CO₂ networks will have to be further extended to cover the largest cities of Europe (and elsewhere) and become pre-operational, e.g., by including them into the existing operational in-situ infrastructures. The data from urban networks will provide emission estimates during times of the day (e.g., night-time) and times of the year (e.g., cloudy days or winter in the high northern latitudes) that will enable temporal continuity between satellite observations.

The difficulty of separating fossil fuel emissions from biogenic fluxes in atmospheric inversions can partly be overcome by including in-situ measurements of ¹⁴C in CO₂ into the inversion systems. Adding observations of ¹⁴C will provide an unambiguous means to distinguish between CO₂ from fossil-fuel and non-fossil fuel sources. Modern organic material contains radiocarbon from cosmic rays and bomb tests, but the emissions from fossil fuel burning are free of ¹⁴C because all radiocarbon has long since decayed away. However, to be useful in inversions the network and thus, the number of ¹⁴C observations need to be increased with a high data standard in terms of accuracy and availability (Levin and Karstens, 2007). Therefore, the systematic sampling of the ¹⁴C isotope will be included during the build-up of a pre-operational system. In its full operational stage (phase 3) the in-situ network including urban CO₂ and ¹⁴C isotope sampling will be fully integrated in an operational data infrastructure.

The modelling tools to infer CO₂ emissions from the atmospheric observations are usually based on the inversion of atmospheric tracer transport models as detailed in Chapter-2. Currently atmospheric tracer transport inversions are used to estimate the net sum of total anthropogenic and natural sources and sinks on both global and regional scales (e.g., Rödenbeck et al., 2003; Broquet et al., 2013). Posterior uncertainties are of the order of 50-100% for the net flux but greater than 100% for fossil CO₂ emissions on national scales mainly because of the small size of the fossil signal compared to the natural uptake and release fluxes. In addition to this reason there are three more factors responsible for the large uncertainty: fast mixing of the fossil signal in the atmosphere, errors in the atmospheric transport modelling and, as mentioned above, the currently inadequate atmospheric CO₂ observation network.

During the build up to the pre-operational system in Phase-2, atmospheric transport models will be further developed in terms of their representation of the transport driven by wind fields and turbulent mixing and computing power should help increase their spatial resolution to be able to better represent emissions hot-spots (~10 km). At the same time these tracer transport inversion systems will be extended to be capable of ingesting observations of ¹⁴C-CO₂ in addition to CO₂ to separate the fossil signal from the natural component. The errors in the atmospheric transport modelling will likely be significantly reduced by further improvements in meteorological modelling, i.e. a reduction of errors associated with surface winds, planetary boundary layer height and atmospheric circulation in general.

There is also added value to be gained from embedding the CO₂ inversion system in a larger atmospheric data assimilation system. Correlations between various species (e.g., CO₂ and CO) can provide additional information on source attribution, but also the assimilation of meteorological observations in the system can reduce the errors in the transport (Massart et al. 2015). This is especially important when using satellite observations of CO₂, which observe the very dynamic synoptic variability of CO₂. The main issue in such a comprehensive assimilation system is the significant difference in time scales of the various processes that determine the atmospheric CO₂ variability. Correctly constraining both the high variability of winds and atmospheric boundary layer processes, and the much slower evolution of surface fluxes in one system is a challenging task.

The fully operational optimal system will combine different modelling approaches for estimating fossil emissions. That is in particular the integration of atmospheric tracer transport inversions based on observations of atmospheric CO₂ concentration with carbon and fossil fuel data assimilation systems (CCDAS & FFDAS, as mentioned in [Chapter-2](#)) based on process understanding of the carbon cycle and census data and additional EO data. First research versions of CCDAS and FFDAS have been presented by Rayner et al. (2005) and Rayner et al. (2010). A CCDAS is capable to integrate data across platforms and atmospheric, oceanic and land reservoirs and thus, potentially uses a whole suite of carbon cycle observations in addition to the atmospheric data to constrain the global carbon cycle (Kaminski et al., 2013). So far these systems are still operated in a research environment, for use in emissions verification systems comprehensive advanced Carbon-Cycle Data Assimilation Systems will be required. They are expected to ingest large amounts of data, routinely diagnose carbon quantities, and provide consistent error diagnostics. FFDAS estimates fossil fuel CO₂ emissions based on the Kaya identity (Kaya, 1990), which relates CO₂ emissions from human sources to population, gross domestic productivity and energy consumption. As an assimilation system, FFDAS generates both an estimate of emissions at high spatial resolution (~0.1°) and an accompanying uncertainty estimate based on the observational uncertainties and some prior information. All of the above methods to estimate CO₂ emissions require prior information. The initial pattern of emissions is critical for the inversion results (e.g., Lauvaux et al., 2008). In Phase-1 of the roadmap towards an operational verification system these prior emissions are obtained from the inventory based bottom-up approach outlined in [Chapter-1](#) as static maps on a spatial resolution of tens of km. The availability of accurate geographically and temporally resolved inventory data will provide better prior estimates of the emissions.

Therefore, during the pre-operational Phase-2 these emission maps will be further developed in terms of their spatial (down to approximately 1 km) but pre-dominantly temporal resolution to capture the diurnal cycle of the fossil CO₂ emissions on a per sector basis. The improved emission fields from inventory data can then be tested against the atmospheric observations, i.e. transport inversions can examine the extent to which atmospheric measurements are compatible with the emission estimates. These prior emission fields ideally are on the same temporal and spatial resolution as the transport model used in the inversion and capture the dominant signals in the emissions. The fully operational emission maps per sector on a high temporal and spatial resolution in phase 3 will then also be delivered together with error estimates.

An operational observation system for fossil CO₂ emissions should contain not only of a set of observations together with an advanced modeling system but, as importantly, also an appropriate data infrastructure including management and processing, and reanalysis capabilities.

Finally, a decision support system should be established by the 2030s in order to guide users and stakeholders in the exploitation of the results of the system, e.g., in terms of analyzing the effectiveness of certain reduction policies, treaty verification, carbon management systems. This decision support system should also help planners in implementing regional or city-scale emissions reduction relevant policies.

A data infrastructure largely exists for other areas in geoscience such as numerical weather prediction or seismic earthquake monitoring but currently, there is no single system for the operational dissemination and archiving of carbon-cycle observations and data products. This has to be built up and integrated in any future CO₂ emissions verification system. A robust data infrastructure system as laid out in Ciais et al. (2014) should ensure the ability to synthesize and integrate carbon observations from a wide variety of platforms and techniques within a coherent modelling framework based on the above-mentioned approaches. Thus, a data management system is required for the operational phase. It will enable access, understanding, use, integration, and analysis and visualization of large volume of diverse data at multiple scales. It will ensure documentation and harmonization of all data sources; most importantly this also includes a full account of realistic uncertainties and sampling biases in all measurements. If possible the production and dissemination of data should be automated to facilitate the compliance with given data and metadata standards. An essential element is a data policy that provides full and open access to the observational data, and ensures interoperability of the system and gives due credit to the data providers. The data infrastructure will also regulate data preservation, i.e. all data including value-added products and the algorithms used to produce them, have to be archived when the data sets are finalized.

The concrete costs of an optimal operational system are hard to estimate partly because of the many different components (observational network, modeling capabilities and facilities, data infrastructure) of the system and partly because cost estimates can only be based on current prices.

The notional costs for the space segment should be of the order of current cost of a line of Sentinel satellites part of the Copernicus programme (about 300 M€ for the first mission, recurring units about half of that). In addition costs are related to the modeling component, the extension of the ground-based network as well as the ground-based infrastructure.

6. Towards implementation

Phase-1. Requirements, technical developments and first European CO₂ mission to resolve emissions (2015 to 2025)

From the start of the project, this phase should be requirement-driven, and focused on the integration of existing remote-sensing, in-situ and modeling capabilities, system design and requirements including end-to-end uncertainty assessment, and on the improvement of inventories towards faster update and higher spatial and temporal resolution.

In the early stages, significant stakeholder involvement will be needed and international cooperation should be developed in the context of a global inter-operability of a future emissions monitoring system. A clear and efficient governance will have to be clearly established, logically following (part of) the existing and successful Copernicus program.

During Phase-1, all financial arrangements and technical developments of a space-borne sensor with capabilities to resolve CO₂ emissions should be made, to achieve the launch of a first satellite dedicated to the monitoring of CO₂ emissions in the early 2020s.

Phase-2. Pre-operational (2025 to 2030)

This phase should be a user-driven pre-operational phase lasting up to five-years, centered on the implementation of a new line of European satellite missions, similar to the current Sentinel program. The satellite launched in Phase 1, will deliver the first data to test and optimize a top-down operational fossil CO₂ emissions monitoring system. International cooperation including data sharing agreements and the definition of optimized plans for the set-up of a global observation system, will enable the assimilation of additional satellite data, e.g., from US, China and Japan.

The atmospheric transport models required to operate the inversion procedure will be able to address high enough time and space resolutions to make it relevant for emissions monitoring at mega-city scale.

Later on, follow up CO₂ satellite missions, together with improved in-situ capabilities will be combined with inventories to deliver the first sets of improved emission estimates at national and subnational scale.

Phase-3. Operational (beyond 2030)

This phase will include additional in-situ networks capabilities in Europe, USA, Asia and emitting countries, to monitor trends and spatial details of fossil fuel CO₂ emissions. In this phase, routine observations of in-situ tracer data (radiocarbon in CO₂) enabling to separate fossil emissions from natural fluxes, and a combination of space-borne sensors, most probably LEO satellite imagers possibly complemented by GEO imagers will feed a fossil emissions operational data assimilation system.

The full inversion procedure will be entering its operational stage in order to ingest and to optimize the observations delivered by the various in-situ networks, emission inventories and available space-borne data.

In Phase-3 dense top-down sampling of the fossil fuel CO₂ signal in the atmosphere, in space and time, will enable to track fossil fuel emissions with a level of accuracy compliant to policy needs.

Composition of the expert group



Philippe Ciais

Leader of the LSCE research department on Biogeochemical cycles and transfers and Professor at the University of Versailles – St. Quentin and at the Beijing University (Gif sur Yvette – France)

With his research background on inverse modeling of CO₂, he worked on understanding the carbon cycle over the last 20 years. He led the preparation phase of the ICOS infrastructure in EU, and the IPCC AR5 Carbon and other Biogeochemical Cycles chapter. P. Ciais is among the top five most cited scientists in the field of climate change.



David Crisp

Leader of the NASA Orbiting Carbon Observatory-2 (OCO-2) Science Team (Jet Propulsion Laboratory, California Institute of Technology, Pasadena – US)

Over the past 30 years, he provided scientific instruments for several flight projects including the Soviet/French/Japan/US. He contributed to NASA's technology and astrobiology programs. As Principal Investigator of the Orbiting Carbon Observatory (OCO) mission, he also served as the Science Lead of the NASA Atmospheric CO₂ Observations from Space (ACOS) team.



Hugo Denier van der Gon

Senior Scientist and project leader at the TNO department Climate, Air & Sustainability (Utrecht – The Netherlands)

With his background on non-CO₂ greenhouse gas emissions such as CH₄ from rice paddies and indirect N₂O from agriculture, he is currently involved in the emissions monitoring of CO₂ and CH₄ from cities. He leads the European TNO-MACC inventory of air pollutants, greenhouse gases and aerosols, focusing on analysis and source apportionment for source sectors like residential combustion, shipping, road transport and energy industries.



Richard Engelen

Deputy head of the ECMWF Copernicus Atmosphere Monitoring Service (Reading – UK)

He is responsible for the operational global data assimilation and forecasting services of the Copernicus Atmosphere Monitoring Service. With his background in satellite retrievals, data assimilation and forecasting of atmospheric composition, he focused on remote sensing and data assimilation of atmospheric CO₂.

Martin Heimann

Director at the Max Planck Institute for Biogeochemistry (Jena-Germany), professor at the University of Jena and of Helsinki. Over the last four decades he worked on analyzing and modeling the carbon cycle and its interaction with the physical climate system. With his background in meteorology and climate modeling he coordinated FP3 and FP4 projects on the quantification of the European carbon balance, its spatial and temporal variability and driving processes.



Greet Janssens-Maenhout

Project leader at the JRC Institute of Environment & Sustainability (Ispra – Italy – European Commission)

With her background on energy engineering, she leads the Emissions Database for Global Atmospheric Research, supplying global grid maps to a large users' community and time series to IEA and UNEP reports. DG CLIMA is served with GHG trend analyses and DG ENV with emissions for the UNECE Task Force on Hemispheric Transport of air pollution.



Peter Rayner

Professor at the University of Melbourne, Data Assimilation and Biogeochemistry (Melbourne – Australia)

After his climate studies with an energy balance climate model, he focused on atmospheric inverse modeling, the ocean carbon cycle and the global carbon cycle and terrestrial modeling. He is director Clean Air and Urban Landscapes Hub and coordinated an infrastructure project for measurement of the European carbon cycle.



Marko Scholze

Assoc. Professor at the Lund University, Dep. of physical Geography Ecosystem Science (Lund – Sweden)

With his background in terrestrial carbon cycle modeling, he coordinates the Space Science Institute Working Group on Carbon Cycle Data Assimilation, contributes to the ICOS Carbon Portal and several ESA projects on remote sensing of vegetation and soil moisture. He was principal investigator of several FP7 projects on global carbon observation, changes in carbon uptake by oceans, ecosystem shifts, and model-data fusion for carbon cycle quantifications.



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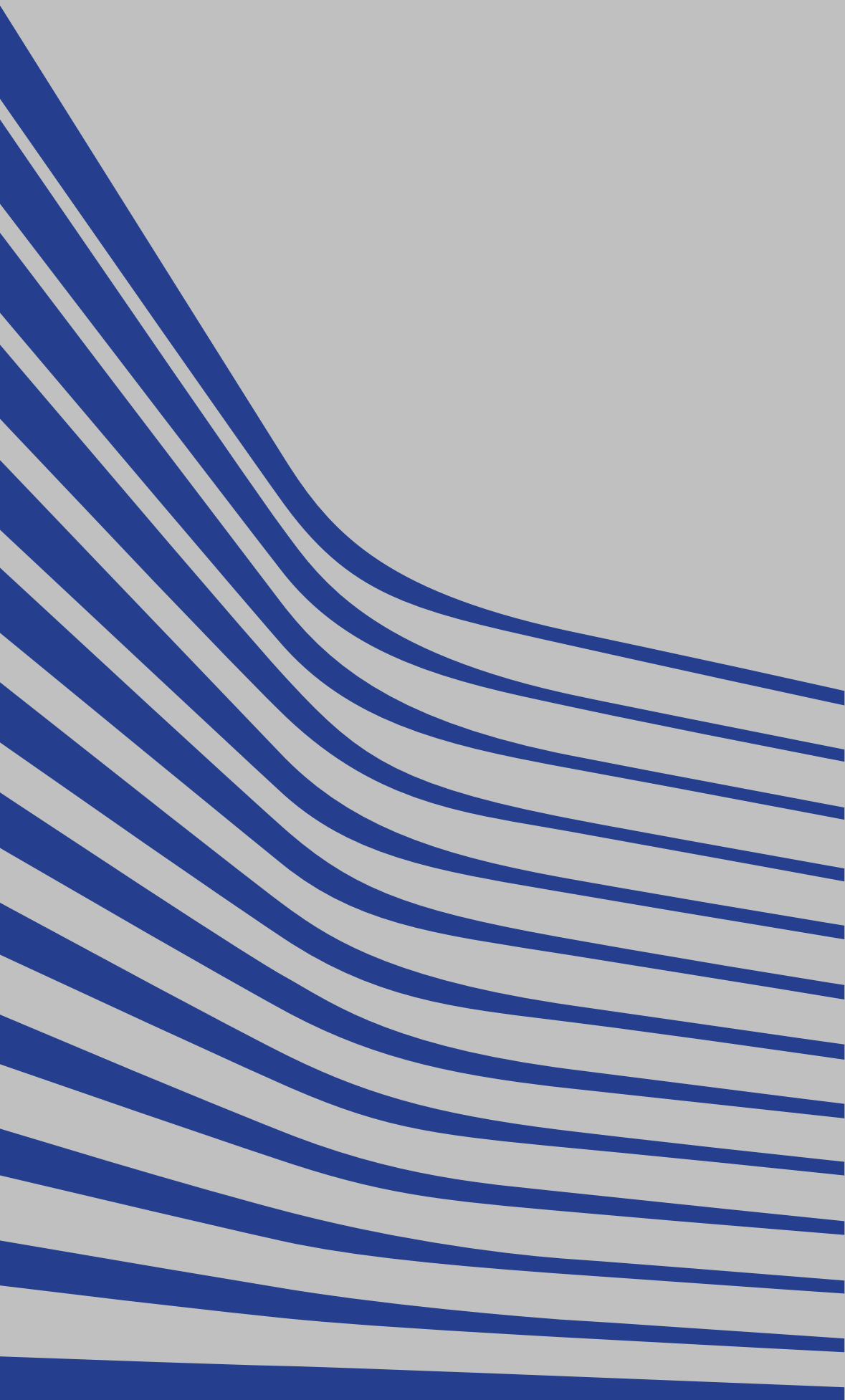
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